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THE EQUATORIAL ELECTROJET SATELLITE AND SURFACE COMPARISON

A Collection Of Papers Presented To The
Fourth International Symposium
On
Equatorial Aeronomy*

DECEMBER 1972

GSFC — GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

*Submitted for publication in the Journal of Atmospheric and Terrestrial Physics

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Edited by
J. C. Cain
and
R. E. Sweeney

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PREFACE

The following series of papers summarizes those that dealt with the OGO-4 and 6 observations of the equatorial electrojet and the comparisons with surface observations. These papers were discussed at the Fourth Equatorial Aeronomy Symposium held at the University of Ibadan, Nigeria and submitted to the Journal of Atmospheric and Terrestrial Physics in essentially the present form.

Some of the papers have been severely critized in the review process and there have been several lively disputes on interpretations (some of the reviewers comments are noted herein). However, it was thought better to distribute the material in this form as soon as possible so that a more thorough analysis and resolution of the questions can be made in time for the forthcoming symposium on low level satellite surveys to be held at the second IAGA General Scientific Assembly in Kyoto, Japan (9-21 Sept, 1973). Contributions to this symposium with further work on the equatorial electrojet as seen by low orbiting spacecraft would be welcome.

Editors

THE POGO DATA

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ABSTRACT

During intervals in 1967 - 1970, the OGO-4 and 6 spacecraft made over 2000 traversals over the equatorial electrojet in the altitude range 400-800 km when local times were between 9 and 15^h. These spacecraft carried total field magnetometers making measurements to an accuracy of 2^γ with a sample rate greater than once a second. ΔF values, the deviations of these observations from an internal reference model, were plotted for a 30° band about the equator, and the characteristics of the electrojet effect in the data were investigated. This effect was characterized by a sharp negative V-signature of some 16-19° in width and a variable amplitude. The minimum of this signature was found to lie within 0.5° of the dip equator with a slight northward shift noted at the longitude of Huancayo. The jet amplitudes were normalized to 400 km amplitudes and observed to be highly variable in time. Amplitudes over the longitude range 50 to 90°W averaged 60 percent higher than elsewhere, as expected, due to the weaker main field. However, though the scatter of amplitudes is high, the expected minima in east Asia was not evident. It was speculated that this could be due to a less conducting upper mantle in this area.

Numerous anomalous cases were observed, usually during magnetic disturbance. Although some of the largest eastward jets were observed at these times, there were also instances when the jet was absent or weakly westward. One such westward jet occurred during the recovery phase of a storm when there was no activity in the auroral zone.

Other instances appeared where the V signature in ΔF spanning 20° in latitude became instead a triple V (VVV) covering about 40°. One interpretation would be the presence of an eastward current in the magnetosphere affecting the total field over about 20° of latitude in which the jet could be detected. The whole structure is imbedded in a reduced field of the characteristic DS shape.

INTRODUCTION

The term "equatorial electrojet" was coined by Sydney Chapman (1951) to describe the ionospheric current then conjectured to be responsible for the anomalously large variation of Sq(H) observed near the magnetic dip equator. This variation had been observed with the establishment of the Huancayo observatory in 1922 and discussed by A. G. McNish (1937) in terms of an enhanced Sq due to the large deviation of the dip equator from the geographic at that longitude. The basis of the theory showed some advance by the recognition of J. Egedal (1947) of Peterson's result that the ionospheric conductivity could be greater at Huancayo because of the smaller value of the magnetic field. The essential theoretical explanation was then provided first by Hirono (1952) and later by Baker and Martyn (1952), who used estimated ionospheric parameters and showed that the east-west effective conductivity could be greatly enhanced at the dip equator by the possibility of maintaining a vertical electric field.

With interest in this phenomena high and impetus from the IGY, more observing stations were established, including temporary nets of several recorders across the equator. Such studies as those by Onwumechilli (1959) and by Forbush and Casaverde (1961) confirmed earlier estimates by workers such as Martyn (1949) that the current was concentrated over a narrow band about the dip equator and that its intensity was highly variable from day-to-day.

Measurements by rocket experimenters, first by Singer, Maple and Bowen (1951) and later by Cahill (1959) and numerous others, established that the altitude at which the conductivity was maximum occurred near 100 km over the dip equator.

More theoretical work on the possible current structures by Untiedt (1967) and by Sugiura and Poros (1969) established that the east-west current flow is accompanied by two cells of toroidal flow in the meridian plane near the equator.

Radar measurements near Peru (Cohen and Bowles, 1963) have established that an instability occurs in the electrojet and is detectable after the current rises past a threshold value. The effect of this phenomena on electrojet theory appears to have not yet been developed.

THEORY AND MODELS

The most recent development of a model electrojet is that of Sugiura and Poros (1969) who showed that for a reasonable model of ionospheric parameters and magnetic field, and some assumptions on the behavior of the eastward current and boundary conditions, the electrojet width is of the order of 400 km flowing over an altitude range from 100 to 120 km. Other facets of their results include the presence of an equally strong meridional component of flow in two cells which center 2-3° on each side of the dip equator in a direction so that the horizontal flux is eastward inside the south cell and westward within the north. The longitudinal variations in the strength of the main magnetic field result in a ratio of about 1.7 in the intensity of these currents, from the strongest near Peru compared with the weakest near India. This ratio applies both to the strength of the meridional flow as well as that of the eastward current.

The presence of such a current and its limitation in altitude to the 100-120 km range is consistent with such rocket experiments as those by Davis, Burrows and Stolarik (1967).

Numerous authors have attempted to define a reasonable model of the eastward current distribution from the magnetic variations. Chapman (1951) considered the field patterns at the surface that would be produced by infinitely long currents in the form of a line, uniform band, and band with a parabolic distribution. The use of the infinite line current approximation is justified by the fact that most of the contribution comes from the current nearest the observer. For traversals at 400 km altitude, 90 percent of the field is contributed by currents within 1000 km east and west. At 800 km altitude the contribution is 70 percent for currents within 1000 km. Onwumechilli (1967) has used another function:

$$J = J_o \frac{a^2 (a^2 + \alpha \xi^2)}{(a^2 + \xi^2)^2}$$

which allows for the change of the shape of a symmetric current from that of a near parabolic or gaussian distribution ($0 \leq \alpha \leq 2$) to one where there is a possibility of a westward current outside the main positive eastward core. No one has yet attempted to use such theoretical models as that of Sugiura and Poros (1969) to see whether there is agreement in the shape of the curves, and if so, what might be the parameters. Their model does predict a very weak westward current.

The modelling of data profiles from either satellite or surface observations is influenced by the effect of induced currents. This question has not yet been seriously attacked for the case of the electrojet other than to follow Chapman's (1951) lead in overestimating their effect by the use of an infinitely conducting layer at some depth. The effect of a more realistic distribution of conductivity has not been applied to this problem. Forbush and Casaverde (1961) used the 250 km depth along with a uniform band current 600 km wide for their data in Peru. Onwumechilli and Ogbuehi (1967) found an equivalent depth of about 200 km for the conducting sheet. None of these estimates are considered by their orginators to be particularly accurate.

The effective width of current from the theoretical model of Sugiura and Poros appears to be of the order to 550 km. Onwumechilli obtains an equivalent width of almost 800 km. The signature of the jet effect in the total field satellite data can be computed from various models by application of the equation

$$\Delta F = |\bar{F}_i + \bar{F}_j| - |\bar{F}_i|$$

where j refers to the jet effect and i to the internal field. Flying the satellite magnetometer over a plane earth with a uniform band current 550 km wide and a conductor at 200 km depth in the presence of a dipole-like field whose dip varies 2° in 111 km gives the curves of Figure 1. These are normalized to a 70γ horizontal field at the surface. More sophisticated models have been calculated with the uniform current model in which the magnetometer is flown at a constant radius over a spherical earth with varying depths and widths of current. The result is essentially the same as that shown.

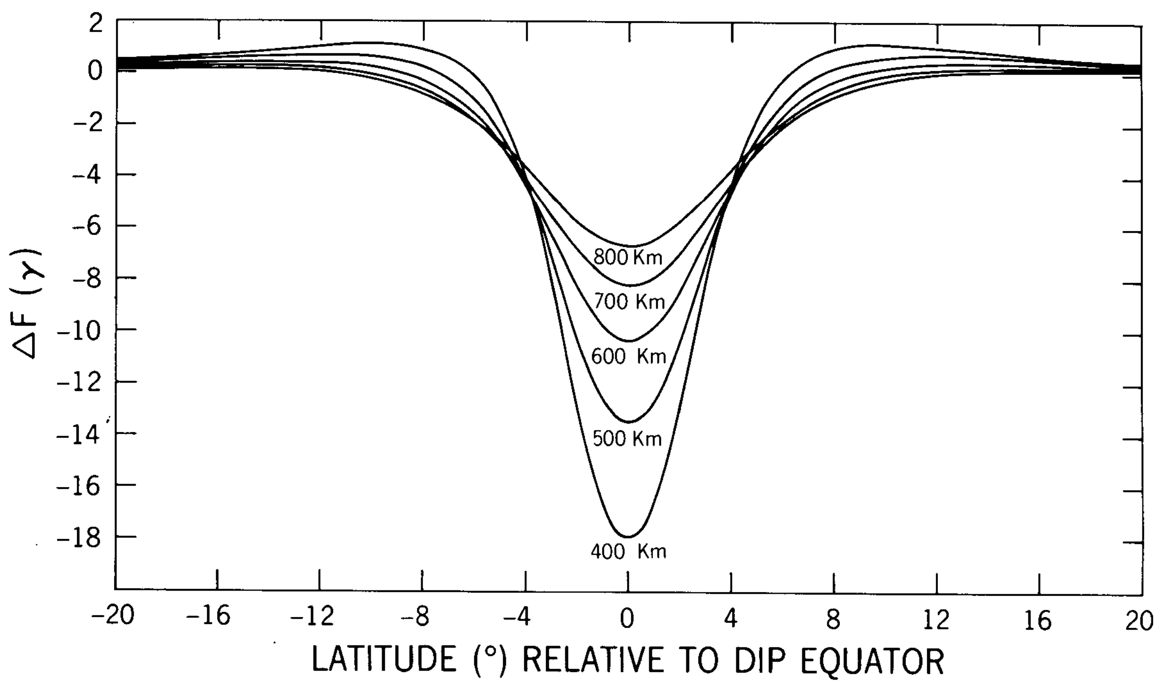

Figure 1. Anticipated ΔF variation expected at several altitudes due to model equatorial electrojet. Model current is uniform sheet 550 km wide at 100 km altitude with image current at 500 km depth. Current intensity is normalized to produce $\Delta H = 70^{\gamma}$ at earth's surface. $\Delta F = |\bar{F}\text{ (dipole)} + \bar{F}\text{ (jet)}| - |\bar{F}\text{ (dipole)}|$.

The additional effect of Sq from outside the immediate jet region is yet to be resolved. Using the classical work of Chapman (Chapman and Bartels, 1940) to represent the expected ΔF variations, we obtain the curve in Figure 2. It is presently not clear from surface data and such results as those of Olson (1970) as to how much of the observed Sq should be modelled in the ionosphere. This is left for further analysis of the POGO data, which should be able to resolve the question. Since the electrojet signature itself is fairly sharp and distinct, it can be at least initially isolated from the broader Sq effect.

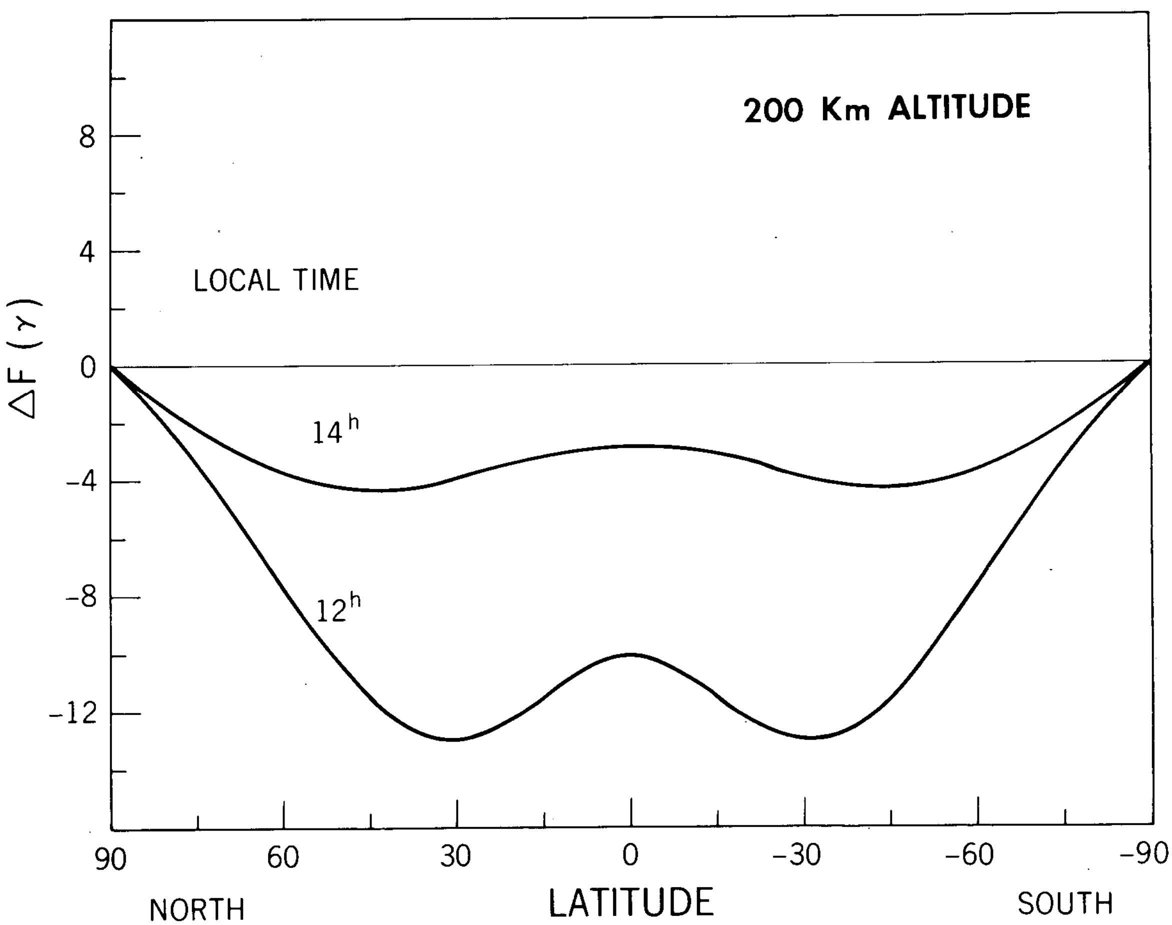

Figure 2. Approximate variations from Chapman Sq function as seen by total field magnetometer above current sheet. Dipole main field assumed. The function used is that given by Chapman and Bartels (1940; page 692) for the mean equinox of 1902.

THE POGO DATA

The POGO series spacecraft included the near polar OGO-2, 4 and 6 launched in 1965, 1967 and 1969 respectively. Each carried a total field magnetometer and observed the field to an accuracy of about 2γ. Reference fields were established from the data (Cain, Hendricks, Langel, and Hudson, 1967, Cain and Sweeney, 1970), which allowed studies of time variations (Langel and Sweeney, 1971).

Since OGO-2 primarily operated only when in full sunlight and only acquired two partial traverses over the electrojet, the discussion here will center on OGO-4 and OGO-6. The characteristics of these orbits relative to equatorial traverses are as follows:

	Altitude Range Over Equator	Angle to Geographic Equator	Approximate Local Time Change Per Day
OGO-4	410-910 km	90°	-6 min
OGO-6	400-1100 km	86°	-9 min

Figure 3 gives the range of local times and altitudes over the equator for the intervals of data collection. During these intervals the data were acquired for almost all traversals except those for which there were mechanical problems or when the tape recorders were being used for spacecraft control functions.

REFERENCE FIELD REDUCTION

The interpolation of the data to provide a base reference for seeing the effect of the electrojet was done by the procedure given by Cain et al. (1967). Its use for internal field definition was discussed by Cain (1971). The character of the jet signature in the residuals ΔF = F (observed) - F (model) does not change significantly from model to model so long as one uses an expansion of the internal spherical harmonic function V of degree n = 9-13* corresponding to about 40° in the minimum wavelength of the field. This fitting scheme has been applied to the data for very quiet intervals emphasizing data taken at local times outside the 9-15^h range where the electrojet is strongest.

*Benkova, Dolginov, and Simonenko (1973) have pointed out that the spatial wavelengths of the ΔF field arise from a spectrum different from those of the potential function V ($\bar{F} = -\nabla V$) since the F computation involves squares of the components. Although the mathematics of this dependence has not yet been worked out, we estimate that the "smearing" of harmonics from V to F is confined to a few orders.

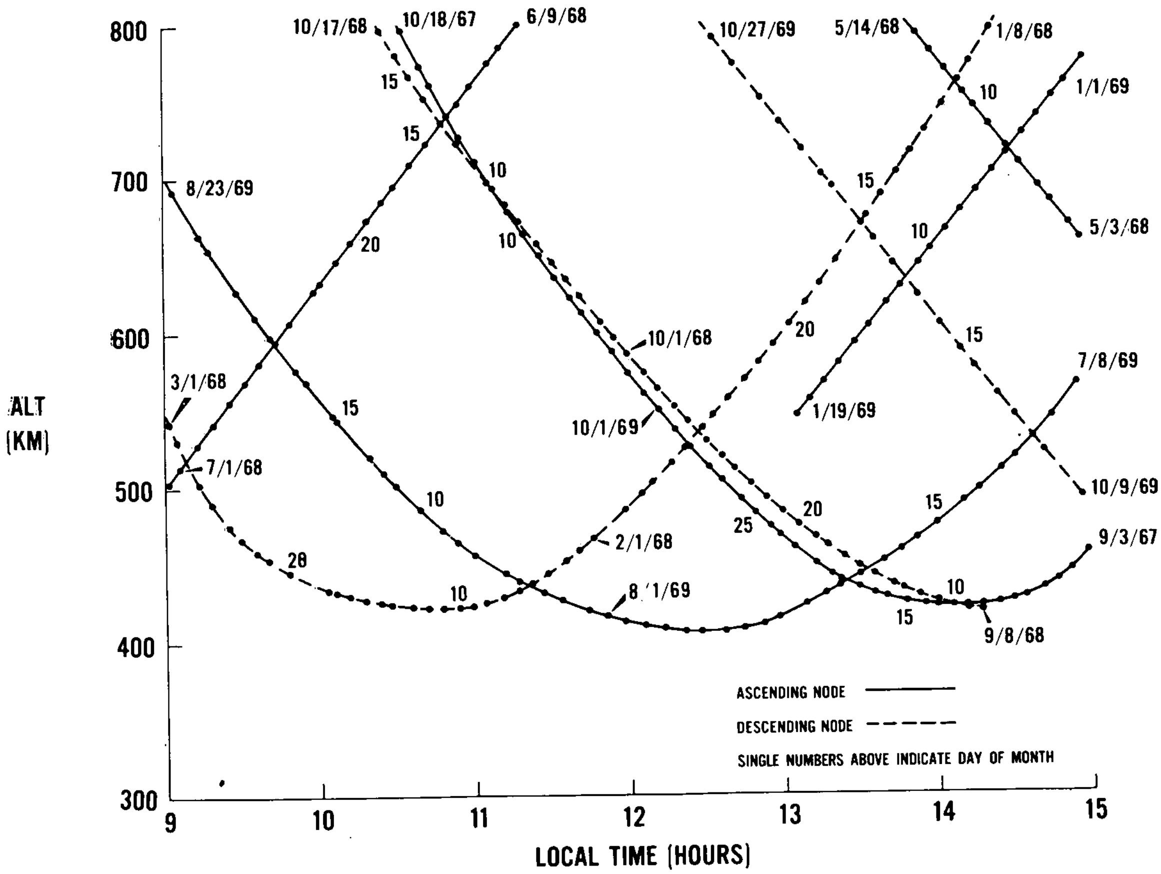

Figure 3. Approximate altitudes (km) and local times (hours) of OGO-4 and 6 equatorial crossings from 3 Sept. 1967 through 27 Oct. 1969.

The results of such a model give oscillations in the ΔF of the order of 3γ with wavelengths perhaps 35°. These oscillations due to the analysis are considered spurious but have not yet been removed since they are of the same order as the time variations and deviations due to orbital error. Also, they begin to approach the instrumental uncertainty of $1-2\gamma$.

IDEAL DATA

The presence of numerous complex magnetic variations in the data often make it difficult to measure the quantitative effect of the electrojet itself. Figure 4 shows an example of a ΔF curve for both a day and night pass across the same longitudes. It is clear that while there is about a 10γ shift between these two curves, undoubtedly due to variations in magnetospheric contributions, the background (~2γ) oscillations are similar. The electrojet signature in the daytime curve is extremely clear.

MAGNETIC ANOMALIES

For the purposes of this paper we will use the term "magnetic anomalies" to mean variations of wavelength somewhat shorter than the 30-35° ΔF oscillations which are residual from the field fitting. That is, they would be variations of a wavelength comparable to that of the electrojet signature and thus constitute interference with interpretations of the jet.

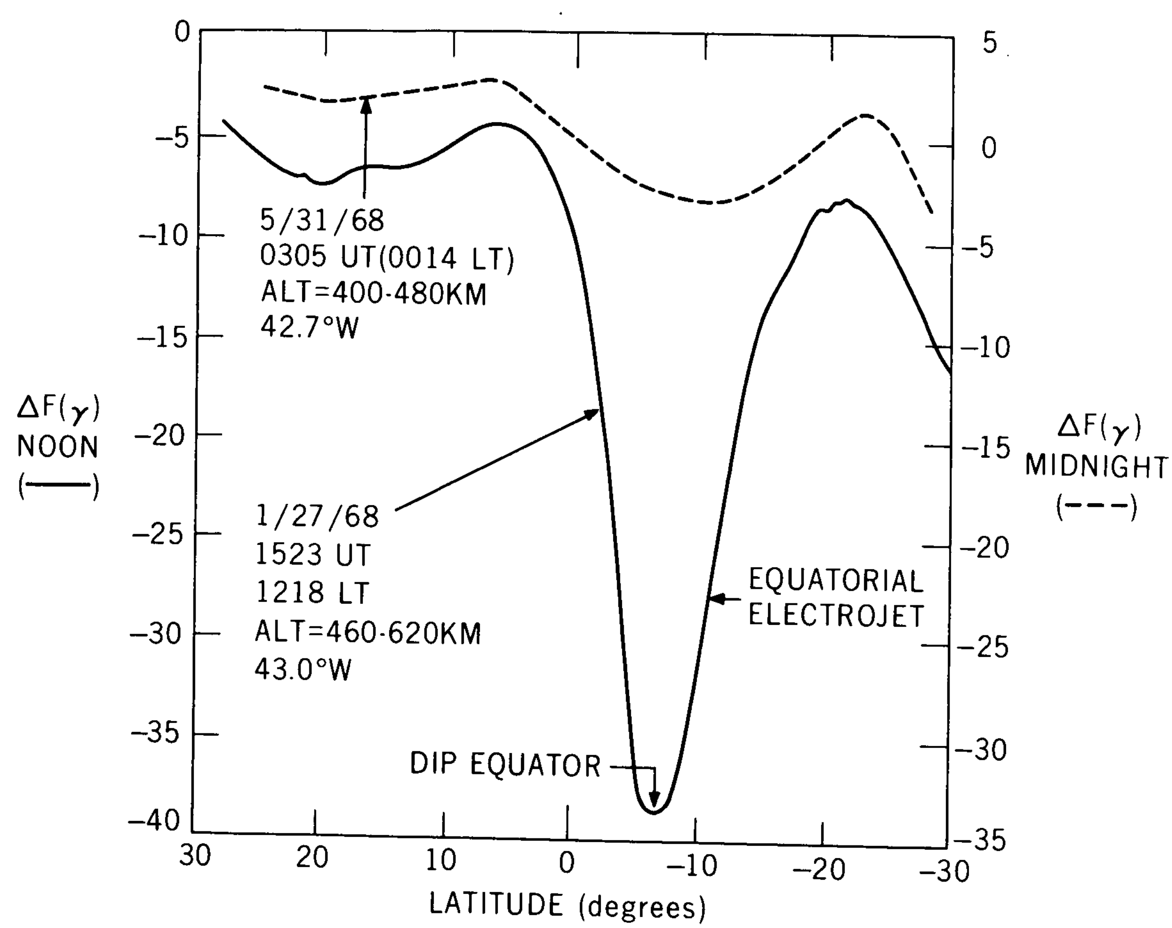

Figure 4. "Ideal" ΔF variation of observed field after subtracting an internal reference model. Shown are two separate traversals over the middle Atlantic and eastern Brazil. Solid curve is a daytime pass showing the "V" signature due to the equatorial electrojet; the dotted curve is from a near midnight traversal showing no electrojet.

Figure 5 is an example where a day pass can be compared approximately with an evening traversal over the same longitude. The troughs near -8° and -26° constitute what might be referred to as "magnetic anomalies." Since the two passes differ in altitude by 50-100 km and longitude by about 20 km, one would not expect an exact match from a fixed surface pattern.

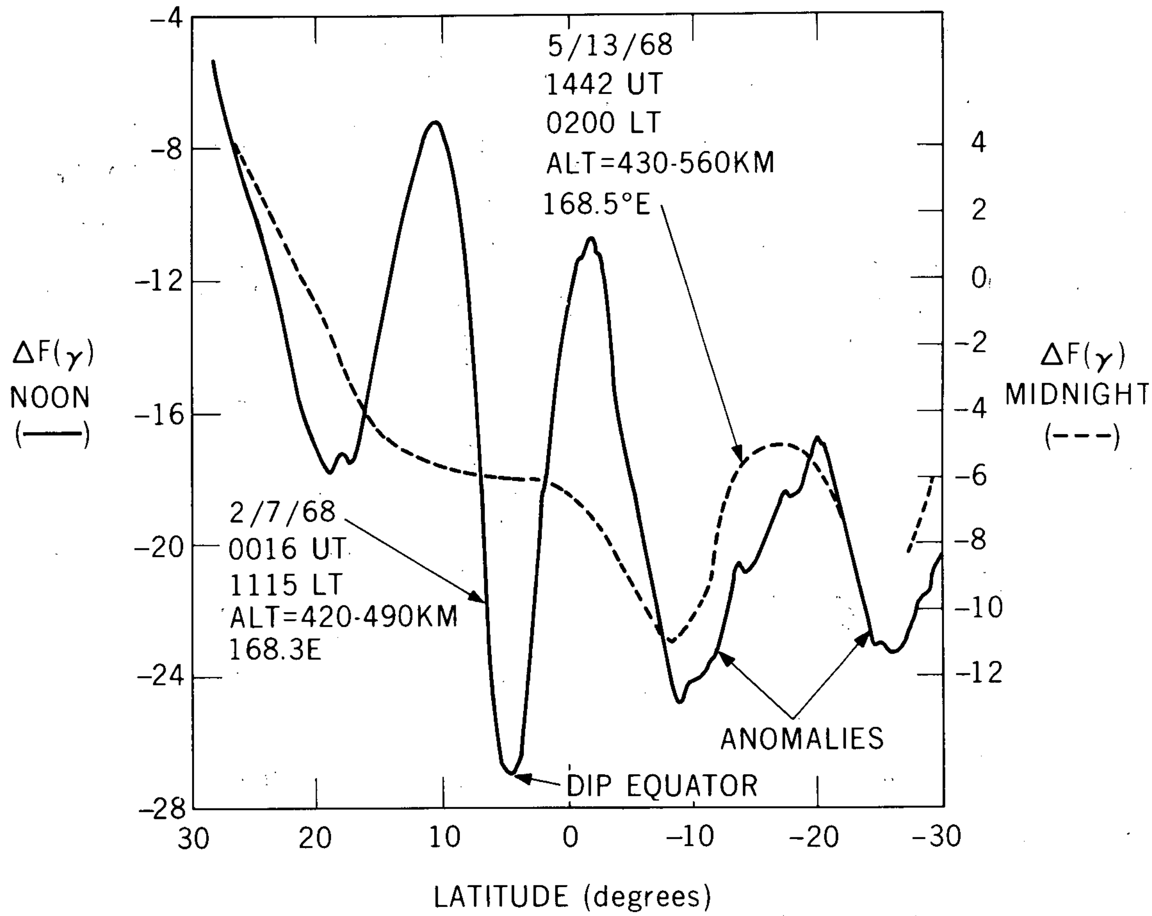

Figure 5. Examples of day and night traversals over western Pacific. Both day (solid line) and night (dashed) show structure from 10° to 30°S probably due to magnetic anomalies. High "shoulders" on each side of electrojet minimum in day trace is atypical.

An anomaly that was found to be more troublesome in the electrojet evaluations is illustrated in Figure 6. Here both a day and night pass over central Africa appear to show the same electrojet signature. This negative anomaly, one of the largest noted to date, is presently being investigated and will be described in more detail (R. D. Regan and W. M. Davis, private communication, 1972).

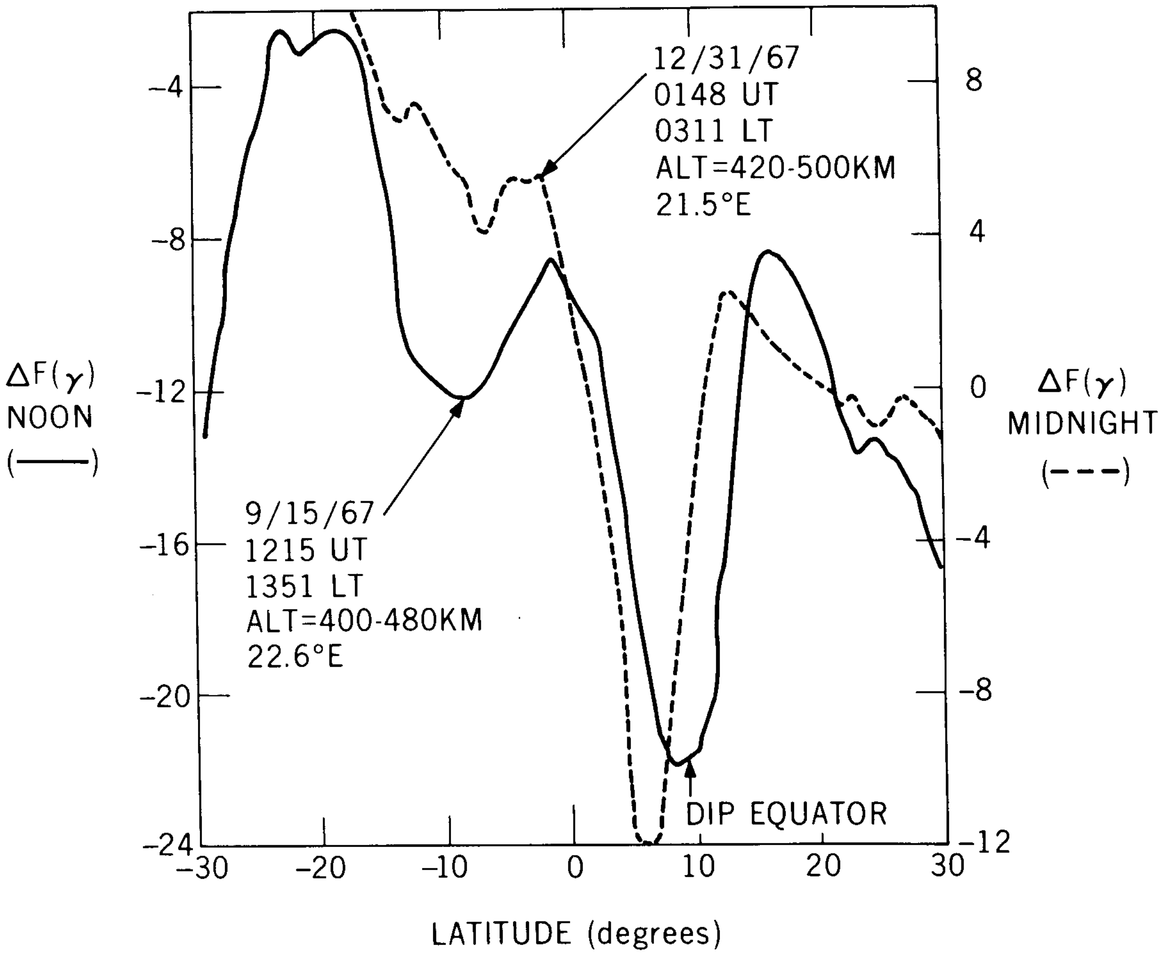

Figure 6. Magnetic anomaly around Bangui (Central African Republic) near position of electrojet on both day and night passes.

MAGNETIC DISTURBANCE

The effect of magnetic disturbance has not yet been studied in detail. However, we can show examples where there appears to be normal negative, or even positive jet signature in the data.

Figure 7 is a traversal over India where there is a negative field due to external sources and a typical electrojet signature. Plotted for reference is a nighttime pass at a lower altitude for the same longitude. The decrease of the field near the equator is of the characteristic form from the (asymmetric) ring current or DS variation as studied by Langel and Sweeney (1971).

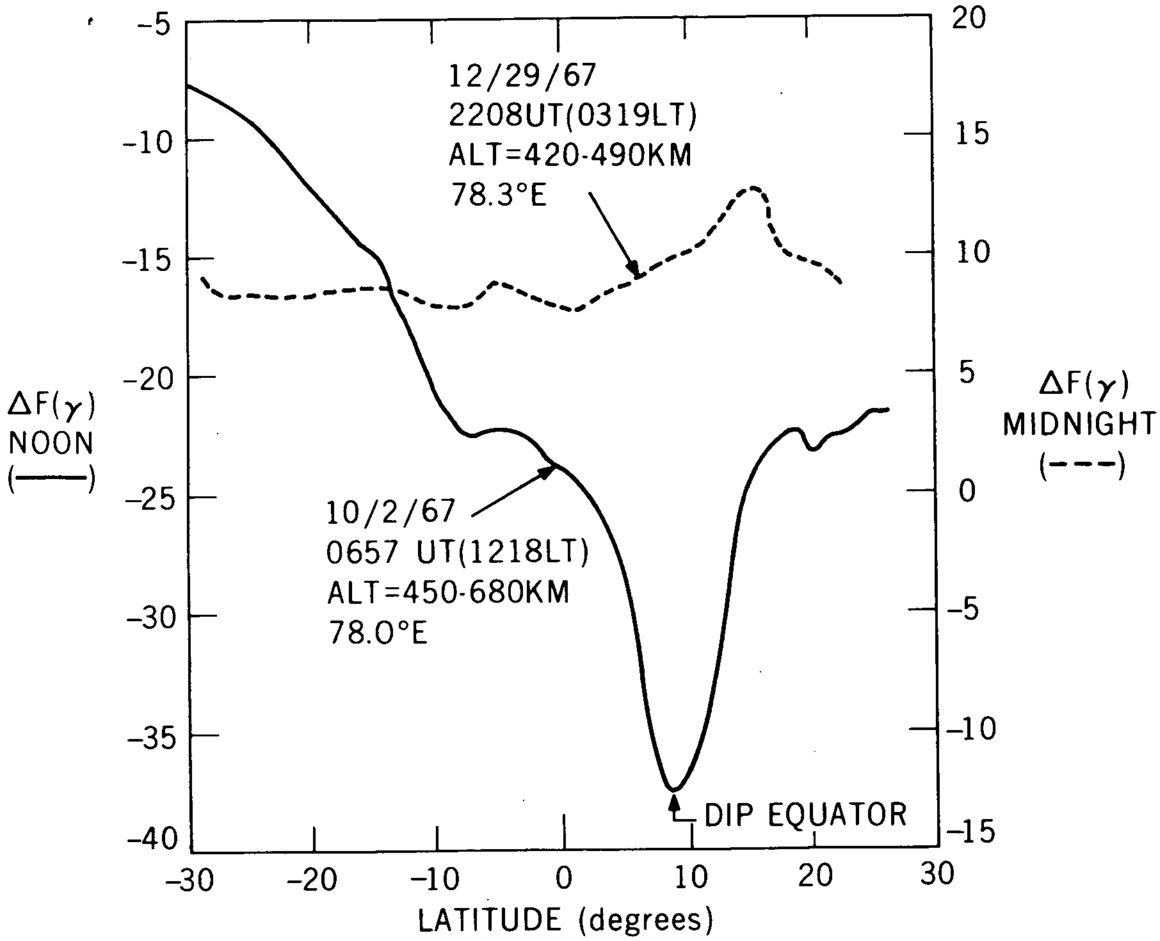

Figure 7. Normal electrojet effect during slight magnetic disturbance (over India).

Figure 8 is a traversal during the recovery phase of a storm at which time Sugiura and Poros (1971) calculate Dst to be -76γ. It appears that, if one smooths the "DS" curve in latitude with the dashed line, the electrojet was a positive 5γ. Another case of an apparent positive effect near the equator is shown in Figure 9 for a traversal just east of Hawaii. Here the difference from the dotted line projection for Dst is a positive 8γ at the dip equator. Dst is fairly constant at about -30γ for several hours on each side of this pass. During this interval the Honolulu magnetic observatory traces are also essentially constant.

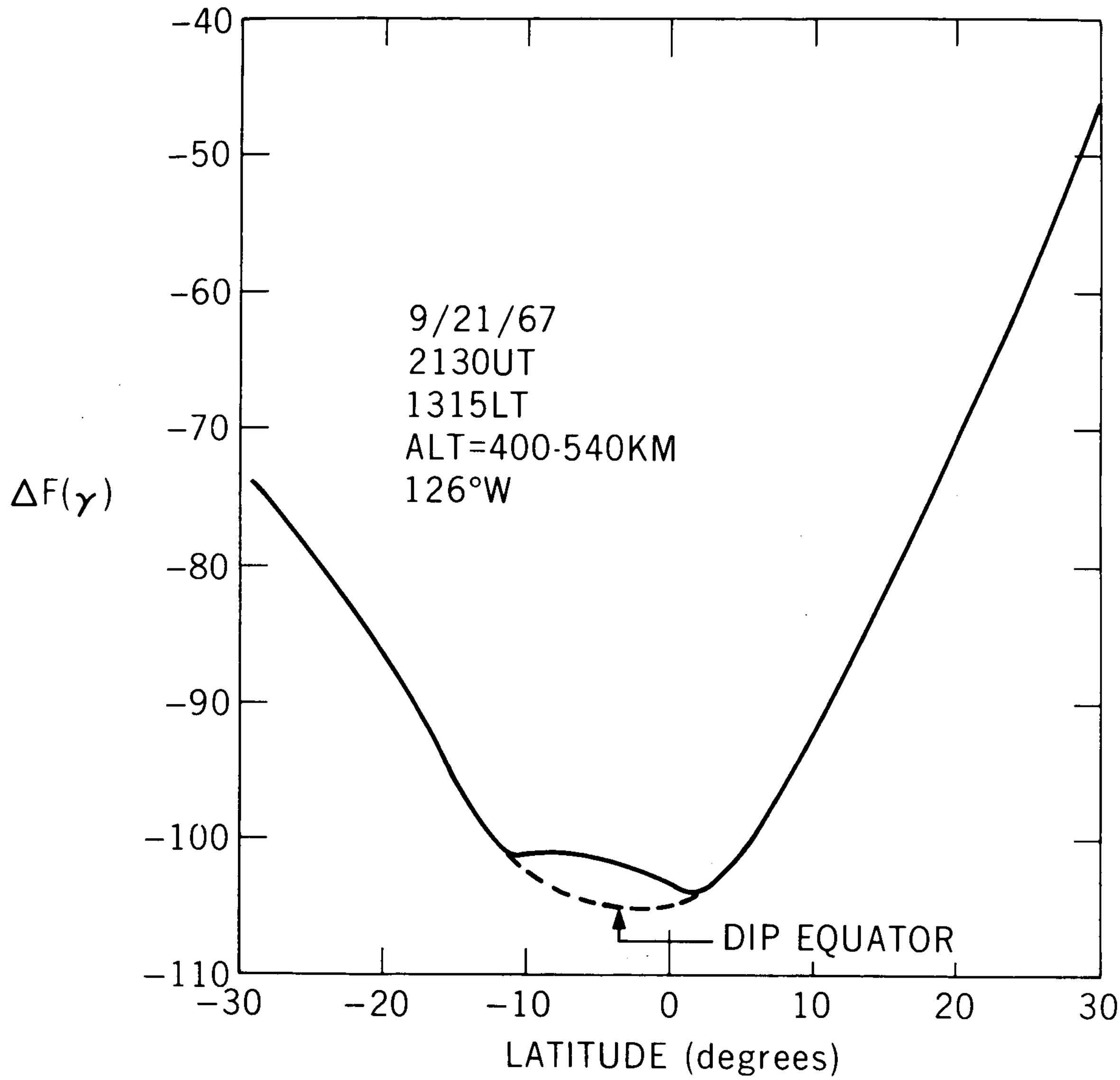

Figure 8. Weak reversed electrojet during recovery phase of moderate magnetic storm (over eastern Pacific).

One might conjecture that this reversal could be due to the low latitude response from an auroral zone substorm in adjacent longitudes. However, an inspection of the magnetogram for the College magnetic observatory shows almost no activity near the time of this pass. While it would be easy to explain this reversal on the basis of a reversal of the neutral wind driving the electrojet, there is no evidence for an Sq reversal at Honolulu. Also, the reversals seem to appear frequently during the decay phase of a magnetic storm implying that it may be a storm related process.

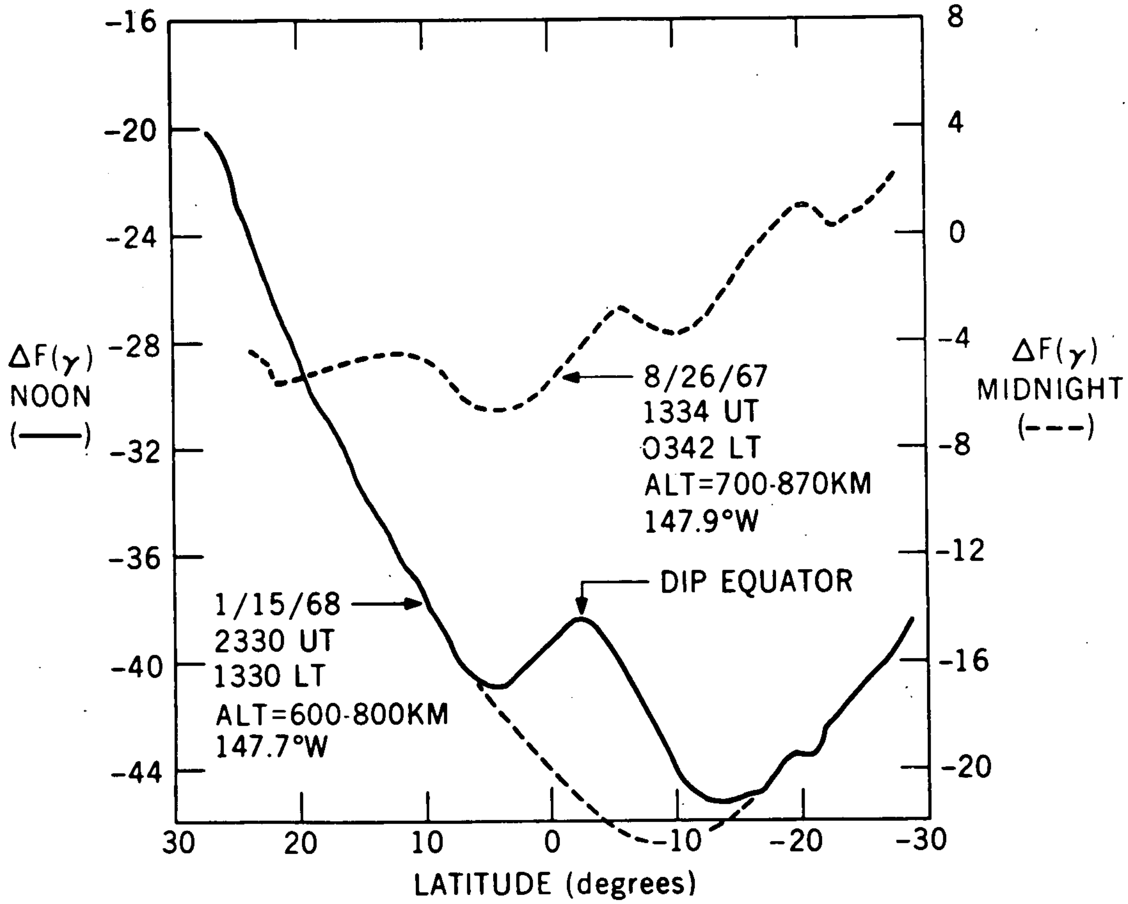

Figure 9. Reversed electrojet during magnetic disturbance (near Hawaii).

COMPLEX CASES

In addition to the apparent electrojet reversals which are frequently characteristic of the recovery phase of magnetic storms, there is another class of "unusual" electrojet signatures that may or may not be related to magnetic disturbance. One such type shows an apparent rise in total field on either side of the normal electrojet signature. This can take the form of the "high shoulders," already illustrated in Figure 5, where there was a slight degree of magnetic disturbance, or a "triple V" shape as shown in Figure 10. (Sugiura and Poros (1971) give Dst = - 37^{γ} at 23^{h} on 9/13/67).

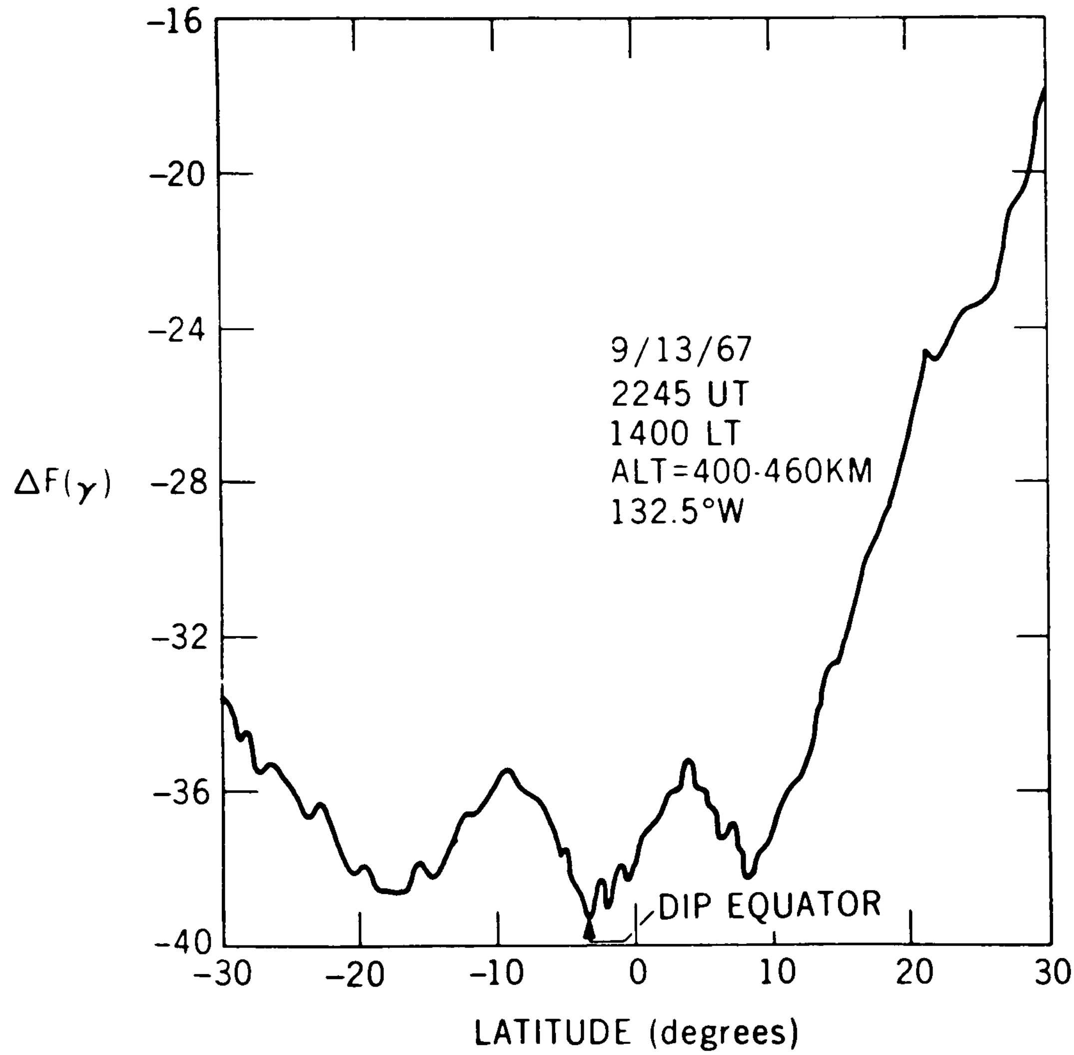

Figure 10. Complex signature in field residuals during moderate magnetic disturbance.

Sometimes, however, the field depressions on one side of the electrojet can be larger than that of the central jet, as shown in Figure 11. For the time period of this pass there is no indication of magnetic disturbance.

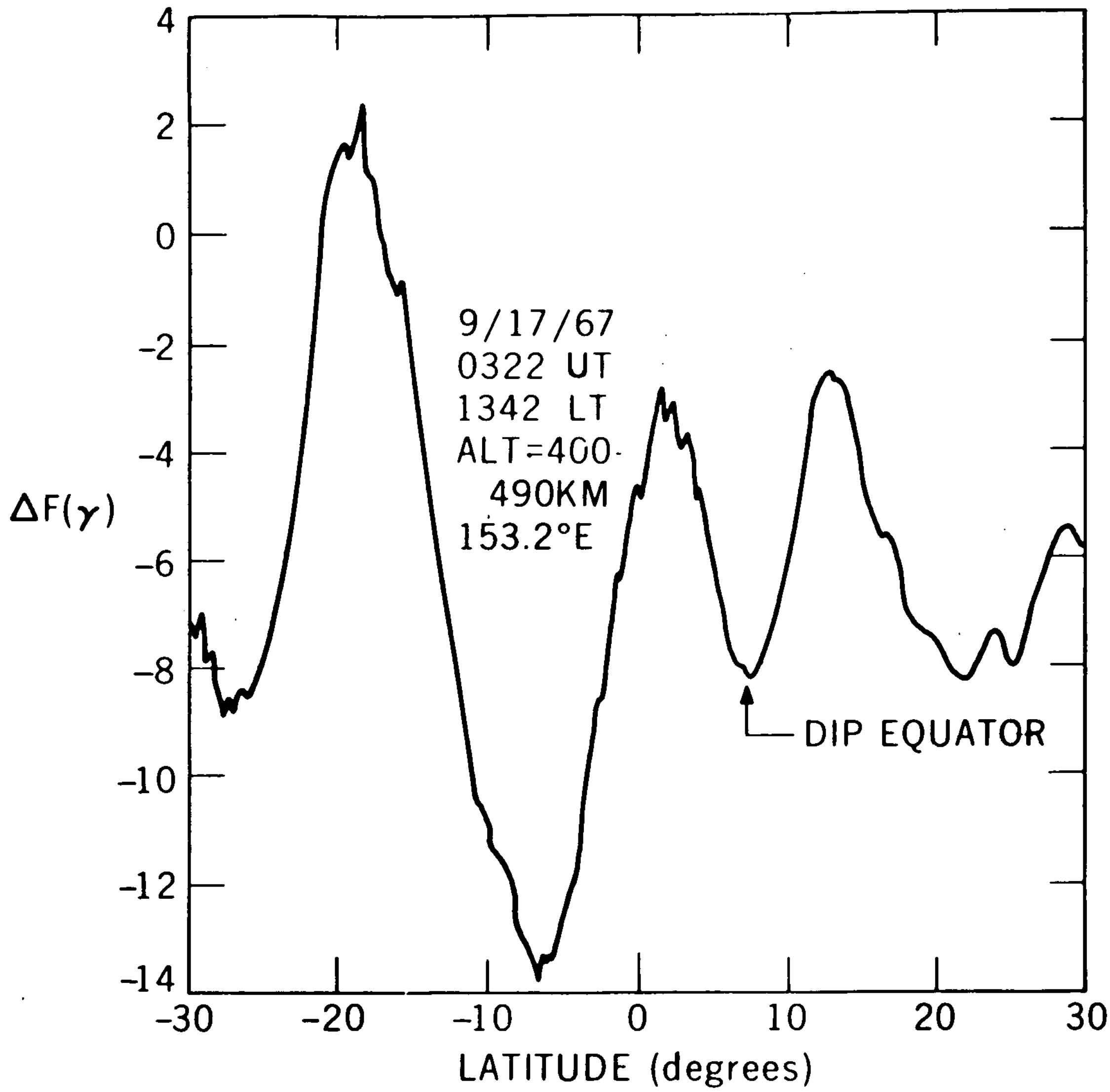

Figure 11. Complex variation with depression on one side of jet exceeding that of the jet.

WESTWARD ELECTROJET

Bartels and Johnston (1940) analyzed the lunar effect at Huancayo and found a modulation of Sq which would periodically result in a jet reversal during the day, though not near noon. This was discussed in terms of the reversal of the driving neutral wind from lunar atmospheric tides. Mayaud (1967) and

Fambitakoye (1971) have found similar instances of reversed, or "counter," electrojet, but without association with lunar phase.

We have already seen examples during magnetic disturbances where it appears that a predominantly westward jet may occur. There are also passes such as Figure 12 where there is a definite positive signature at the dip equator (see the following paper by R. P. Kane in this issue).

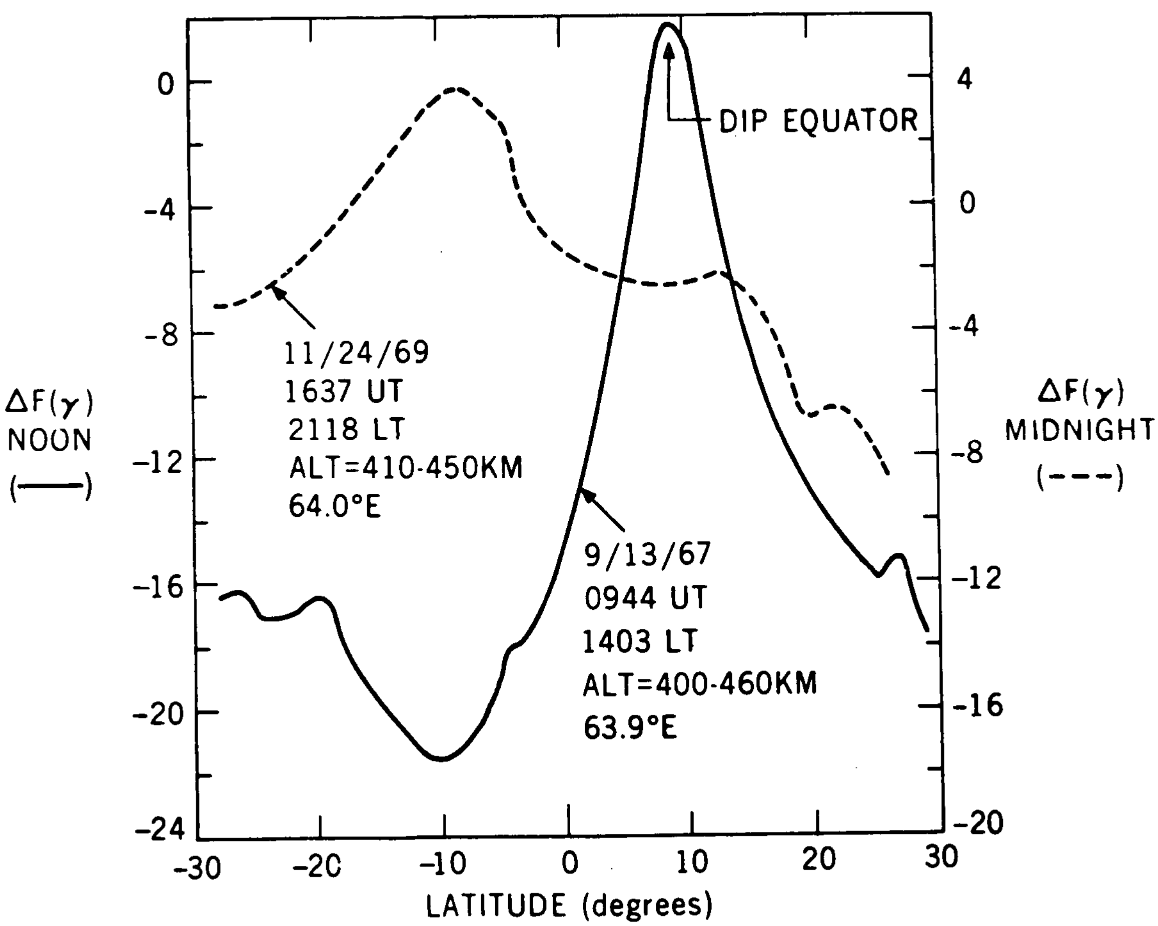

Figure 12. Reversed electrojet over India. Solid curve is day pass showing signature of "counter" electrojet. Dashed curve is a nighttime pass over same longitude.

ELECTROJET DISAPPEARANCE

There are a number of intervals of up to 8 hours during which each POGO traversal over the equator shows little or no electrojet signature. These intervals appear to be usually at times of slight or positive Dst. Figure 13 gives a case where the field shows a broad compression near the equator with no apparent electrojet.

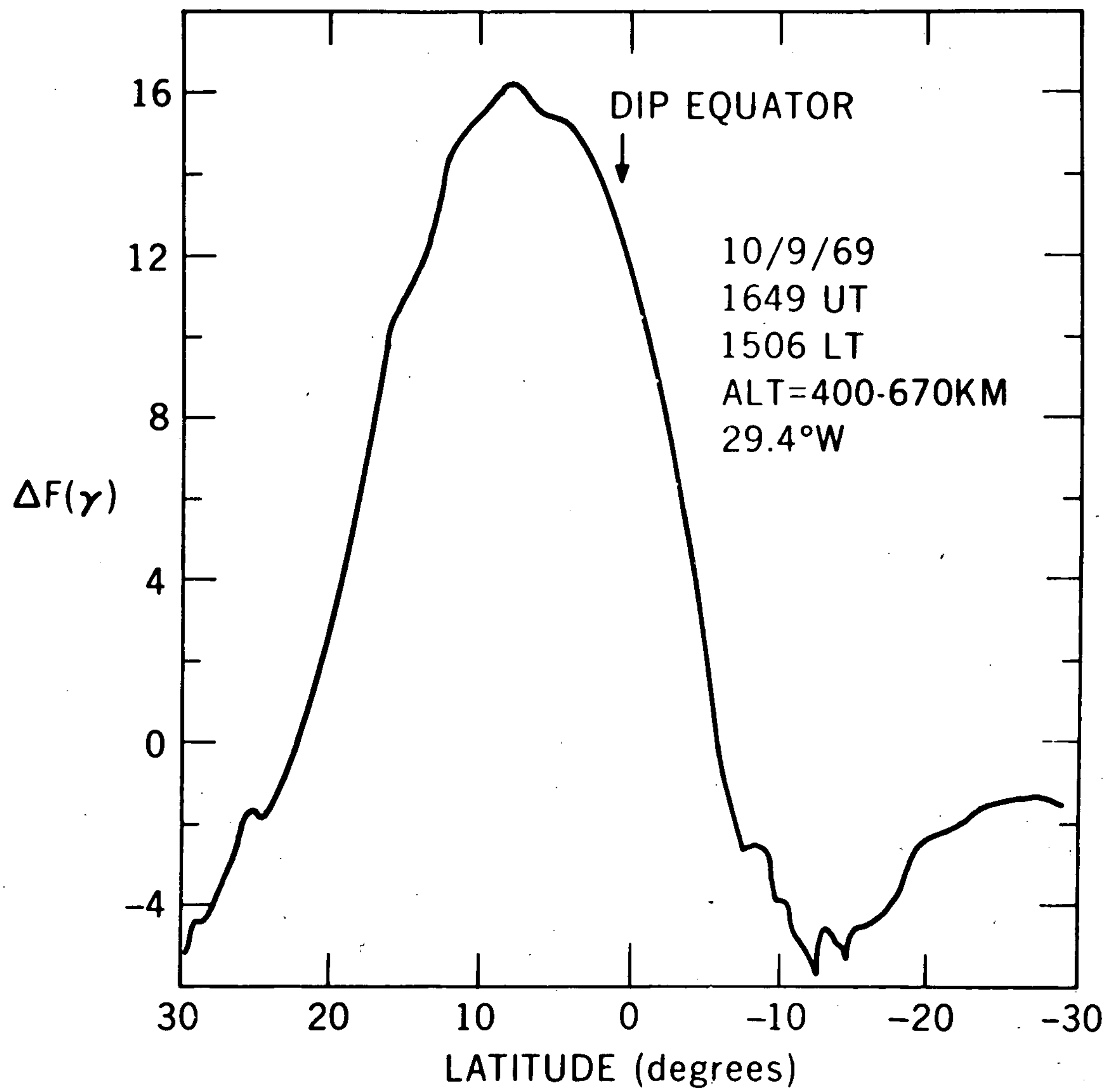

Figure 13. Traversal with no apparent electrojet.

DATA EVALUATIONS

In order to systematize the available information on the electrojet, a semi-quantitative evaluation was made for each pass for the time intervals given by Figure 3. An attempt was made to record the amplitudes of each signature using as a guide such ideal curves as Figures 1 and 4. That is, an amplitude in gammas was read using as base a line connecting the two breaks or shoulders in each curve. These amplitudes were then "reduced" to a constant 400 km altitude using a factor derived from a uniform band current model of width 550 km with an image current at 500 km depth. The amplification factors varied from 3 at 750 km to 2 at 600 km. A tabulation of these estimated amplitudes, their values reduced to 400 km, an estimate of the latitude of the jet minimum, and other qualitative information was given by Cain and Sweeney (1972). This information was sent to most of the following authors prior to the Nigerian meeting.

JET POSITION

The estimated position of the jet minima were statistically analyzed to determine whether there is agreement that the jet center is near the magnetic dip equator. First, we can show the ΔF minima to be very close to the electrojet center.

Assuming the total field to be perturbed by small variations due to the electrojet with a horizontal component $\underline{h}$ and vertical component $\underline{z}$, then

$$\Delta F \approx (H/F)h + (Z/F)z,$$

from which the further approximation $H/F = \cos I \approx 1$ and $Z/F = \sin I \approx I$ near the equator gives $\Delta F = h + I\,z$. If the jet axis and the dip equator at POGO altitude were the same, the minima in ΔF would occur where I is zero and the spacecraft approaches closest to the jet. However, if the field is tilted at POGO altitude directly over the electrojet center, then a minimum in ΔF would occur close to the point where the electrojet field vector would be antiparallel to that of the main field. Given the dip equator at POGO altitude h to be a distance s north of the electrojet axis, it can be shown from simple geometry that the ΔF minimum will occur a distance south of the axis given approximately by the relation $2s\,(h-h_j)/(6370+2h_j-h)$, where h_j = height of the jet. Thus for a dip equator as far as 100 km north of the axis, the southward displacement of the minimum would be less than 10 km or 0.1° in latitude. The jet axis can thus be taken to be coincident with the minima of the ΔF curves.

The position of the minima were then averaged in 2° blocks of longitude and the results given in Table 1 and illustrated in Figure 14.

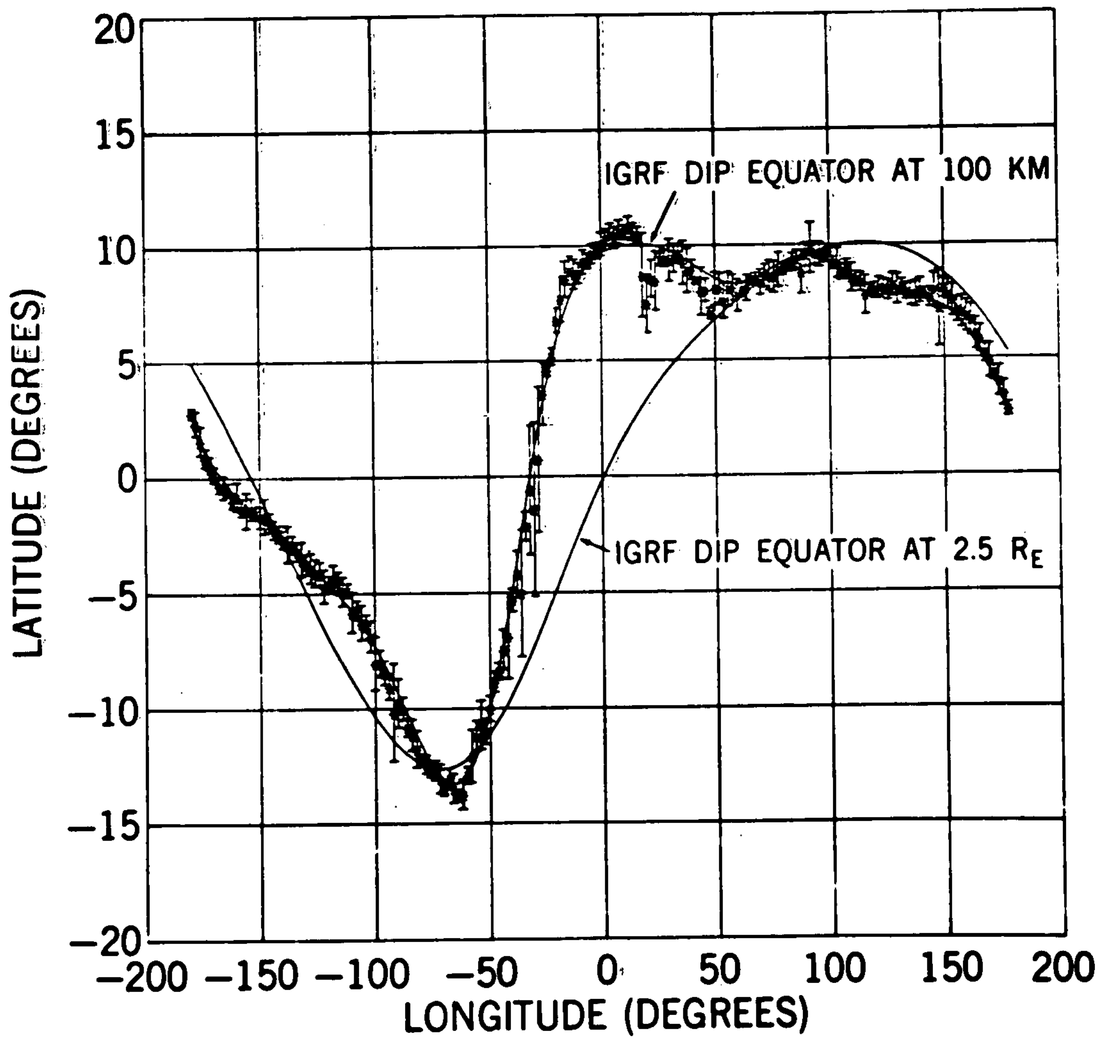

Figure 14. Average latitude of electrojet centers observed by POGO. Error bars give rms of average over 2° in longitude. Dip equator computed from IGRF main field model epoch 1970 (Cain and Cain, 1971) at 100 km and at 2.5 earth radii (Sugiura, 1972).

Sugiura and Poros (1969) computed that the current pattern at 80° west longitude is displaced about 0.5° south of the dip equator (their Figure 2). This displacement is due to the fact that the field is weaker to the south at these longitudes

Table 1

Average Latitudes of Apparent Electrojet Minimums over 2 Degree Longitude Blocks

TABLE 1. AVERAGE LATITUDES OF APPARENT ELECTROJET MINIMUMS OVER 2 DEGREE LONGITUDE BLOCKS

LONGITUDE	LATITUDE	LONGITUDE	LATITUDE	LONGITUDE	LATITUDE	LONGITUDE	LATITUDE
-180	2.8±0.2	-90	-9.8±1.1	0	10.1±0.5	90	9.5±0.5
-178	2.3±0.5	-88	-10.0±0.5	2	10.3±0.4	92	9.8±1.1
-176	1.5±0.6	-86	-10.9±0.4	4	10.5±0.5	94	9.6±0.5
-174	0.8±0.4	-84	-11.2±0.7	6	10.3±0.5	96	9.5±0.5
-172	0.4±0.5	-82	-11.8±0.8	8	10.6±0.5	98	9.5±0.3
-170	0.1±0.3	-80	-12.1±0.1	10	10.6±0.3	100	9.7±0.2
-168	-0.3±0.3	-78	-12.5±0.4	12	10.8±0.5	102	9.2±0.3
-166	-0.4±0.5	-76	-12.7±0.4	14	10.6±0.4	104	9.2±0.7
-164	-0.5±0.3	-74	-12.7±0.4	16	10.4±0.4	106	8.8±0.4
-162	-1.0±0.3	-72	-13.1±0.6	18	6.7±1.8	108	9.0±0.4
-160	-0.8±0.6	-70	-13.5±0.3	20	7.4±1.3	110	8.5±0.6
-158	-1.3±0.4	-68	-13.1±0.4	22	8.5±0.8	112	8.4±0.3
-156	-1.4±0.8	-66	-13.5±0.6	24	8.4±1.3	114	8.3±0.4
-154	-1.4±0.5	-64	-13.8±0.2	26	9.4±0.3	116	7.7±0.9
-152	-1.5±0.3	-62	-13.8±0.6	28	9.4±0.4	118	7.9±0.3
-150	-1.8±0.5	-60	-12.9±0.4	30	9.3±0.9	120	7.9±0.3
-148	-1.7±0.7	-58	-12.1±1.2	32	9.4±0.6	122	8.1±0.5
-146	-2.0±0.4	-56	-11.2±0.7	34	9.6±0.4	124	8.1±0.4
-144	-2.3±0.4	-54	-10.7±1.1	36	9.2±1.0	126	7.9±0.4
-142	-2.5±0.4	-52	-11.0±0.5	38	8.9±1.0	128	8.2±0.5
-140	-2.7±0.4	-50	-10.0±0.6	40	8.9±0.4	130	8.0±0.7
-138	-2.9±0.8	-48	-8.9±0.4	42	8.4±0.1	132	8.1±0.3
-136	-2.9±0.4	-46	-8.4±0.4	44	8.0±1.0	134	7.9±0.4
-134	-3.2±0.4	-44	-7.4±0.9	46	8.0±0.5	136	7.8±0.5
-132	-3.5±0.7	-42	-6.9±1.9	48	7.0±0.2	138	7.8±0.6
-130	-3.8±0.4	-40	-5.3±0.5	50	8.1±0.7	140	7.9±0.5
-128	-3.9±0.6	-38	-4.2±1.0	52	8.1±0.7	142	7.8±0.2
-126	-4.1±0.6	-36	-5.0±2.7	54	7.5±0.8	144	7.6±0.4
-124	-4.2±0.5	-34	-2.2±0.6	56	8.0±0.8	146	7.9±0.8
-122	-4.7±0.7	-32	-0.6±2.8	58	8.1±0.6	148	7.1±1.7
-120	-4.5±0.3	-30	-1.4±3.8	60	7.8±0.7	150	8.0±0.4
-118	-4.4±0.6	-28	0.7±3.1	62	8.0±0.3	152	7.7±0.7
-116	-4.5±0.4	-26	3.6±1.4	64	8.1±0.6	154	7.5±0.7
-114	-4.9±0.6	-24	4.6±0.3	66	8.4±0.2	156	7.1±0.5
-112	-4.9±0.3	-22	5.2±0.4	68	8.5±0.3	158	7.0±0.7
-110	-5.8±0.9	-20	6.7±0.5	70	8.3±0.6	160	6.8±0.7
-108	-5.7±0.4	-18	7.7±1.0	72	8.6±0.5	162	6.6±0.7
-106	-6.3±0.7	-16	8.5±0.8	74	8.6±0.7	164	6.0±0.7
-104	-6.3±0.3	-14	8.9±0.6	76	8.6±0.7	166	5.8±0.6
-102	-6.9±0.7	-12	8.7±0.6	78	8.9±0.7	168	5.2±0.4
-100	-8.0±1.2	-10	8.8±0.4	80	8.9±0.2	170	4.8±0.7
-98	-8.0±0.6	-8	9.3±0.5	82	9.0±0.2	172	4.3±0.3
-96	-8.5±0.5	-6	9.3±0.3	84	9.2±0.4	174	4.0±0.7
-94	-9.1±0.5	-4	9.6±0.4	86	9.3±0.4	176	3.4±0.5
-92	-10.2±2.1	-2	9.8±0.4	88	8.8±1.0	178	2.7±0.3

and that the ionospheric conductivity is inversely related to the field. Cain (1969) calculated that the dip equator moves very little with altitude at this longitude. Thus for this longitude the minima at 400 km altitude would be expected a few tenths of a degree south as predicted from the current model. The average latitude obtained from the POGO data is -12.7 ±0.4°. Since Huancayo is located at -12.3° this places the average value some 40 ±4 km to the south. This estimate is within resonable agreement with the average 27 km south figure obtained by Osborne (1964) using the IGY data of Forbush and Casaverde (1961). However, if we use the 2° inclination over Jicamarca determined by Woodman (1971), the dip equator must be at about 13°S or some 80 km south of Huancayo. Thus the jet axis would be north of the dip equator. This northward tendency has also been pointed out by Burrows (1970) and is not inconsistent with the results of Davis et al. (1967). Both of these last two papers refer to a dip equator at about -13.3° latitude.

Thus, at least at the longitude of Huancayo, the average position is in agreement with surface data although displaced from that expected from a theory which assumes a driving field constant with longitude. One must conclude that this distortion arises either from a tilt in the effective depth of the induced currents or from a gradient of electric field which is stronger to the north.

The apparent discontinuity at 18-24° longitude is fictitious and due to the interference of the Bangui magnetic anomaly (see Figure 6) with the electrojet signature. This cannot be disentangled until the background field has been more completely analyzed to allow modelling this feature.

JET AMPLITUDES

In order to look for systematic variations of jet amplitude, we consider the recent computation of Sugiura and Poros (1969), which gives evaluations of meridional currents at 0, 40, 80, 180, 280° longitude and eastward profiles at 80° and 280°. However, they did not compute estimates at all longitudes which could be then directly applied to our data. We have thus made a rudimentary test computation of the relative conductivity near the dip equator at a constant 100 km altitude using a model ionosphere (R. A. Langel, private communication, 1972). A longitude profile of σ_{yy} was computed and is illustrated in Figure 15. Plotted also on this diagram are the two center values of eastward current ($\boxtimes$ symbols) given by Sugiura and Poros (1969) normalized to our curve at -80° and also the relative values of meridional currents at the five longitudes (⊙) similarly normalized. We have further used the expression given by Davis, Burrows, and Stolarick (1967) for the effective eastward conductivity to compute a model ΔF as seen at 400 km altitude (no image current is used since it would have the same relative effect). That is, the expression

$$\sigma_y = \frac{\sigma_2}{\sigma_1} \sigma_{xy} \sin I + \sigma_{yy}$$

was computed from this ionospheric model where

$$\sigma_{yy} = \sigma_1 + \sigma_2^2 / (\sigma_0 \tan^2 I + \sigma_1)$$

and

$$\sigma_{xy} = \sigma_0 \sigma_2 \sin I / (\sigma_0 \sin^2 I + \sigma_1 \cos^2 I)$$

at a constant 100 km altitude, and the infinite line current approximation was used (no integration with altitude) to compute a ΔF adding into the real field expressed from spherical harmonic coefficients.

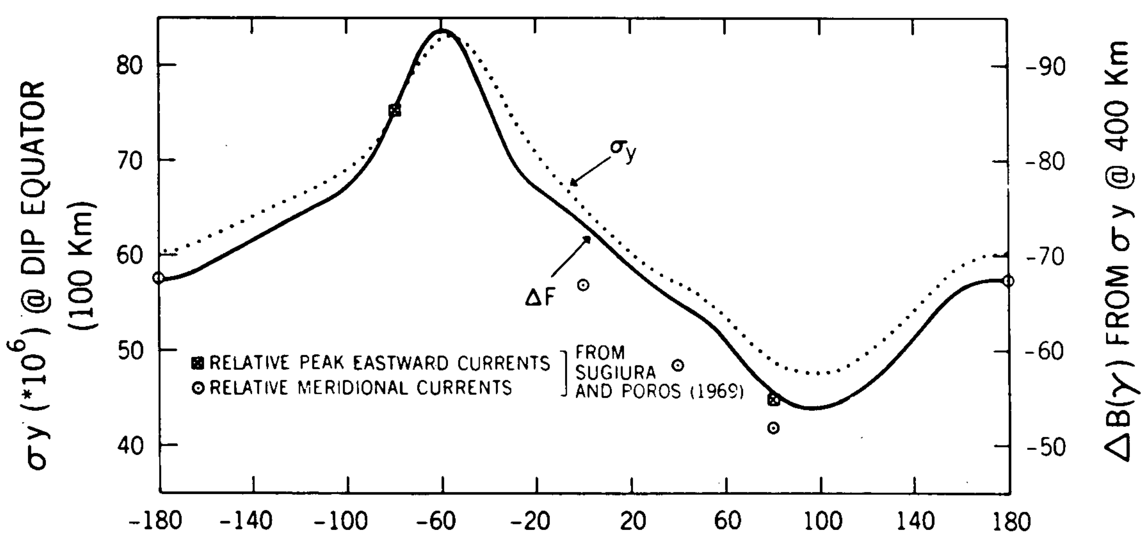

Figure 15. Theoretical relative ionospheric conductivities as a function of longitude.

It is surprising to find that with such poor approximations the two curves and plotted data from the Sugiura and Poros (1969) paper agree so closely.

For comparison with these curves, the distribution of amplitudes (normalized to 400 km and averaged over 30° in longitude) which result from the present assessment of the POGO data are plotted in Figure 16 (solid line) along with the conductivity model of Figure 15 (dashed curve) suitably normalized. The expected maximum in the region from 40 to 80°W is clearly seen. However, the expected trough due to the equatorial field maxima center on the Bay of Bengal is not evident. This plot seems to indicate that instead of a minimum, there is a small maximum in this region. Although the scatter of the data is very large, this result could be interpreted as implying some real systematic effect.

The first interpretation might be that there is some systematic variation related to the distance of the dip equator from the geographic equator. There is undoubtedly such an effect if we are to believe the dynamo theory which regards tidal generated winds as the basic cause of Sq and the electrojet. However, such an amplification should also appear over Africa which appears to have an even lower amplitude. Since the data are taken over several seasons, a seasonal effect would tend to be smeared out. Thus, unless there are systematic changes in the wind patterns at 100 km that would make them relatively stronger near 100° longitude than elsewhere, we must consider that there is some systematic change in the induced currents with longitude. Table 2 gives the results of a model calculation where both the width w of the electrojet and the depth d to the image current are varied. It shows that a given current intensity can result in a stronger jet signature if the image plane is moved to a lower level. Thus, if the Huancayo and African areas are represented by image planes at 200-250 km, then the 100° longitudes could have the amplitudes increased a third to account for the measured averages by dropping the equivalent depth to ~450 km. Such a variation would imply considerable longitudinal inhomogeneity in the composition of the upper mantle.

CONCLUSIONS

It is too early in the analysis to draw very many conclusions from these data. It is clear from these manual inspections of the ΔF curves over the dip equator that although the basic physics of the phenomena are probably correct, there are innumerable variations whose origins are less clear. The most puzzling is the presence of the complex "high shoulder" or "triple V" structure near the equator. If one only used ionospheric currents, the model might be of an eastward jet imbedded in a regional westward flow. Also, until the true character of the general Sq pattern at a particular instant is more clearly identified,

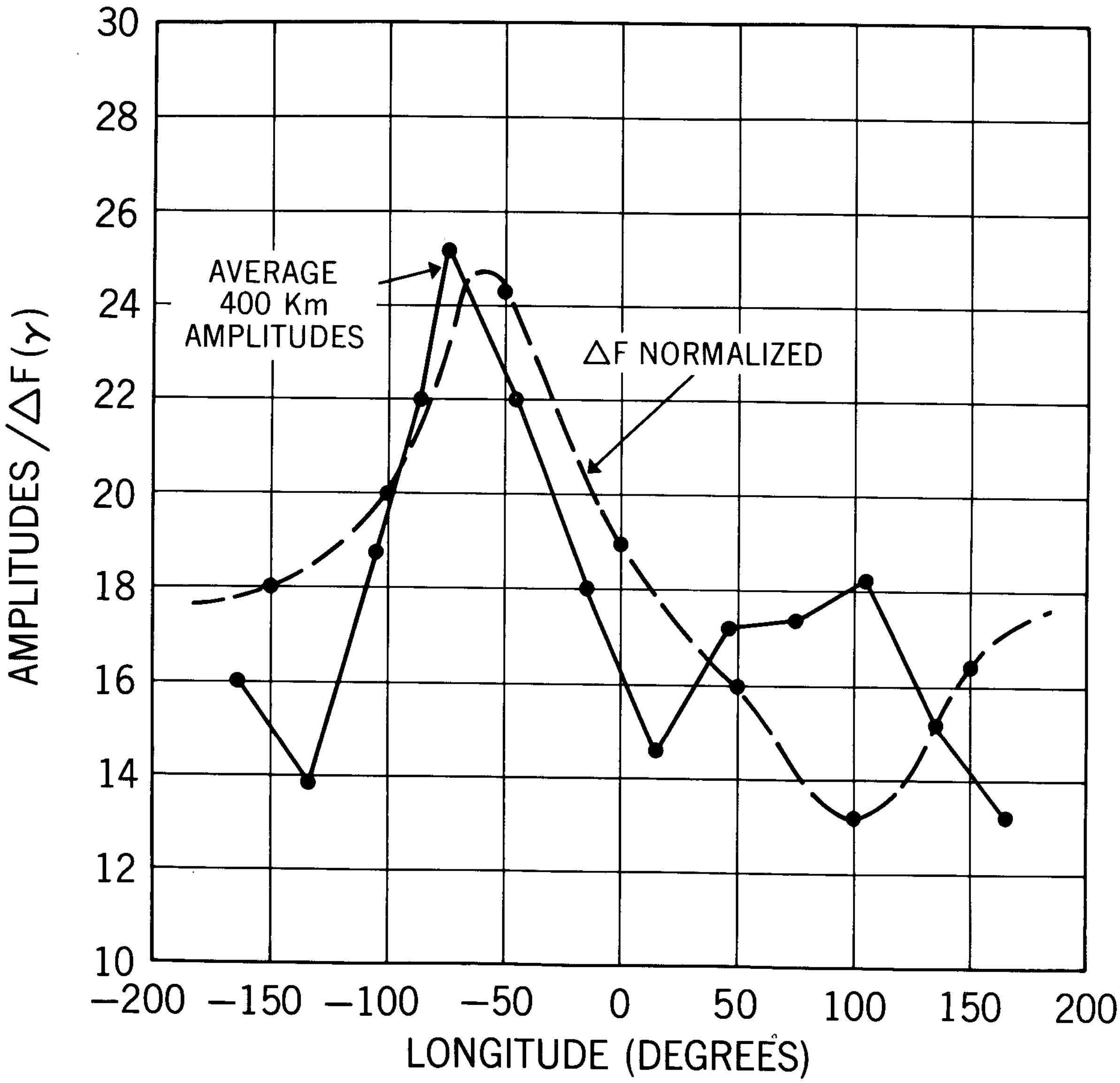

Figure 16. Comparison of averaged POGO electrojet amplitude normalized to 400 km and ΔF obtained from conductivity model of Figure 15. POCO averages taken over 30° in longitude.

one cannot discount the possibility of multiple foci or a fine structure to Sq. Further, the possible influence of the magnetospheric variations has yet to be determined.

The present results of this study, which are extended somewhat by the surface comparisons following, indicate that the jet position follows the dip equator except for small but real and unexplained excursions. Also, the amplitudes east of India not being as weak as present theory could imply that the conductivity of the upper mantel in this area is anomalously low. The further definition of more accurate model representations of these data should benefit future study in such diverse areas as the upper mantle conductivity and the behavior of the magnetosphere and ionosphere, including the neutral winds near 100 km altitude.

ACKNOWLEDGEMENTS

We wish to acknowledge the excellent services of Mr. Yong Deuk Chung of Consultants and Designers, Inc. for assistance in the detailed evaluations of the electrojet amplitudes and positions. Also, R. A. Langel provided us with an ionospheric conductivity model and M. Sugiura was helpful in clarifying points regarding theory.

Table 2

Variations at 400 km. in Signature of Delta-F Curve from Electrojet Model Centered at Dip Equator Using Uniform Sheet Current of Width W (100 km. Alt) and Image Current of Width W and Depth D. Longitude = 80 Degrees. Delta-H = 70 Gammas at Surface.

Delta-F Minimum (Gammas)

		W (km.)					
		500	600	700	800	900	1000
D (km.)	0	-5.4	-5.6	-5.7	-5.6	-5.5	-5.3
	-200	-11.9	-12.8	-13.3	-13.5	-13.5	-13.4
	-400	-15.6	-17.0	-17.9	-18.5	-18.7	-18.8
	-600	-17.9	-19.7	-20.9	-21.8	-22.3	-22.6
	-800	-19.5	-21.5	-23.0	-24.1	-24.8	-25.3
	-1000	-20.6	-22.9	-24.6	-25.8	-26.7	-27.4

COMPARISON OF GEOMAGNETIC CHANGES IN INDIA AND THE POGO DATA

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ABSTRACT

Using the data obtained from POGO, the amplitude of the electrojet signature is compared with the daily variation amplitude of the quantity ($H_{TR}-H_{AL}$), i.e., the difference in the H values at the equatorial station Trivandrum (TR) and the low latitude station Alibag (AL).

METHOD OF COMPARISON

Assuming that within 15° longitude difference, the nature of the daily diurnal variation pattern does not change appreciably, the best estimate of amplitude of the electrojet signature at any particular local time when the POGO traversed the electrojet region as given by Cain and Sweeney (1972) should be directly comparable with the ground observed electrojet strength at the same local time. For ground observations we use the equatorial station Trivandrum (76°E, 1°S Dip, geomagnetic latitude -1.0°) and the low latitude station Alibag (73°E, 25°N Dip, geomagnetic latitude +9.6°) and for POGO, the amplitudes referring to about 60° - 80°E longitudes.

The changes in the H values observed at any equatorial station need not necessarily be changes in electrojet strength. Mangetospheric changes, both isotropic D_{st} as well as asymmetry effects are recorded. However, since the source of the magnetospheric effects is far away from the earth, (about 4 earth radii, though occasionally it may approach as near as 2 earth radii), its effect on ground has a weak latitude dependence, about cos θ where θ = geomagnetic latitude. Hence, a station like Trivandrum under the electrojet will have about the same magnetospheric contribution as a low latitude station outside the electrojet influence like Alibag (cos θ = 0.985). On the other hand, the ionospheric effects at these two locations would be different, those at Trivandrum due to electrojet being about 3 times those at Alibag (Maeda, 1963). Thus, the subtraction of H values at Alibag from the H values at Trivandrum hour to hour would yield a quantity ΔH = H(TRI)-H(ALI) which would be free of magnetospheric effects. Since a part of the ionospheric effect is also eliminated, we add to ΔH the average Sq variation at Alibag obtained for consecutive 2 or 5 monthly periods as the average variation of quiet days (Ap = 0 to 7). Thus hourly values of a quantity Sd_I = H(TRI)-H(ALI)+Sq(ALI) are obtained which give the best estimates of the electrojet strength at Trivandrum.

For every hour of every day in 1967, 1968 and 1969, Sd_I at Trivandrum was obtained. It was found that it had the familiar daily variation pattern of almost constant (base) values from 00 to about 06 L. T., a rise up to about 11 L. T., normally a fall up to about 17 - 18 L. T. but occasionally a drop at 15 - 16 L. T. amost touching or sometimes dropping below the 00 - 06 L. T. base values (reverse electrojet; Gouin and Mayaud, 1967, 1969) and later a constant value roughly the same as the 00 - 06 L. T. base value. Hence all Sd_I hourly values of any day were expressed as deviations from the mean of the 00 - 05 L. T. values of the same day. These deviations ΔSd_I do represent then the actual electrojet strength in units of gamma. Since only hourly vaues were available, values at in-between periods were read out by linear extrapolation. (Thus, the value at 1530 L. T. was obtained as a mean of values at 1500 and 1600 L. T.). Since the best estimate of the amplitude of the electrojet signature given by Cain and Sweeney (1972) is also obtained as the excess effect at the equator in comparison to the values on either side outside the electrojet, we feel that ΔSd_I is directly comparable to the same.

To allow for the fact that all traverses were not at the same altitude, we obtained normalized amplitudes by multiplying by a factor ($ALT/\overline{ALT}$) where ALT was the actual altitude and $\overline{ALT}$ was 520 km, the average altitude for the whole set of data with us. Thus, all amplitudes were normalized to a constant altitude of 520 km.

RESULTS

Figure 1 shows a plot of ΔSd_I (Trivandrum) versus the POGO normalized amplitudes of electrojet signature. Their subjective estimates of the amplitude uncertainty are indicated on the diagram as horizontal error bars for some selected points for the POGO amplitudes.

The whole data set of about 120 days is divided into three groups corresponding to Ap = 0 to 7 (quiet days), 8 to 15 (moderately disturbed days) and exceeding 15 (disturbed days) and further into five L. T. groups corresponding to the traverses occurring between 09-11 L. T., 11-12 L. T., 12-15 L. T., 13-14 L. T. and 14-16 L. T. Thus, in all 3 x 5 = 15 groups are made and Figure 1 shows the plots for these 15 groups separately. Centroids are joined to the origin to give the average slopes as indicated.

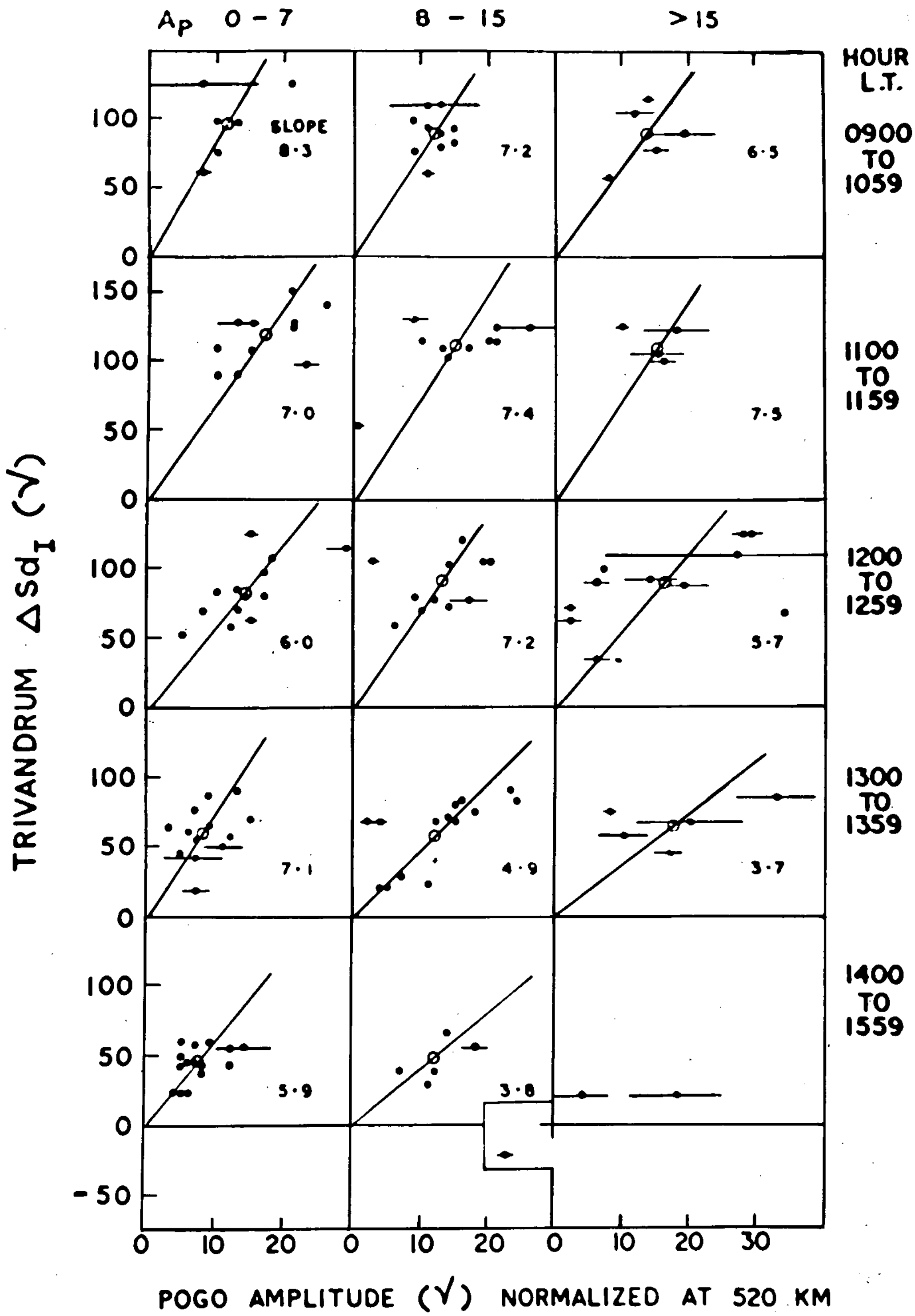

Figure 1. Plot of ΔSd_I (equatorial electrojet strength) at Trivandrum versus POGO electrojet amplitudes normalized to an altitude of 520 km.

The following may be noted:

(1) In many cases, the scatter is rather large. The average slope changes from group to group being in general smaller for higher Ap and/or later local times. The subjective errors mentioned by Cain and Sweeney (1972) are rather large, sometimes as much as 50%. But even allowing for such large errors, a straight line relationship is not always obvious.

(2) Of particular interest is the phenomenon of disappearance or reversal of electrojet which manifests itself as very low or negative values of ΔSd_I. As can be seen from Figure 1, ΔSd_I for Trivantrum were always larger than about 50 gamma for 0900 - 1200 L. T. However, for later hours and particularly for about 1500 L. T., very low ΔSd_I are obtained on some days. On one occasion viz. Sept 13, 1967, the ΔSd_I values was negative (-22 gamma) at 1400 L. T. and could be interpreted as a counter (reverse) electrojet. This reversal is seen in Figure 12 of the preceding paper by Cain and Sweeney as a positive signature of about 10γ. The traversal is shown in our Figure 1 as negative POGO amplitudes in the high Ap, 14-16 L. T. group.

(3) On some days, POGO amplitudes were very low (less than 5 gamms) but ΔSd_I were several tens of gamma.

(4) In Figure 2 we show sample plots of ΔSd_I for a few selected dates. Reversed electrojet effects are visible in some cases, mostly in the afternoon but sometimes in the early morning too. The POGO traverses are at local times indicated by the vertical bars, the heights of which correspond to the POGO amplitudes multiplied by the appropriate slopes shown in Figure 1 corresponding to the group to which the date belongs. Thus, POGO amplitudes are directly comparable to ΔSd_I. In Figure 2(a), ΔSd_I are larger than the equivalent POGO amplitudes while in Figure 2(b), POGO amplitudes are larger than the ΔSd_I. In particular on Sept. 13, 1967, in the afternoon, ΔSd_I shows a counter electrojet which is reflected in the POGO amplitude also as a large reversal.

DISCUSSION

These results are very intriguing indeed. Several possibilities for the discrepancies can be suggested. For the ground-based observation, we have assumed that H changes at Alibag and Trivandrum will be almost similar for magnetospheric effects and roughly in the ratio 3 to 1 for ionospheric effects.

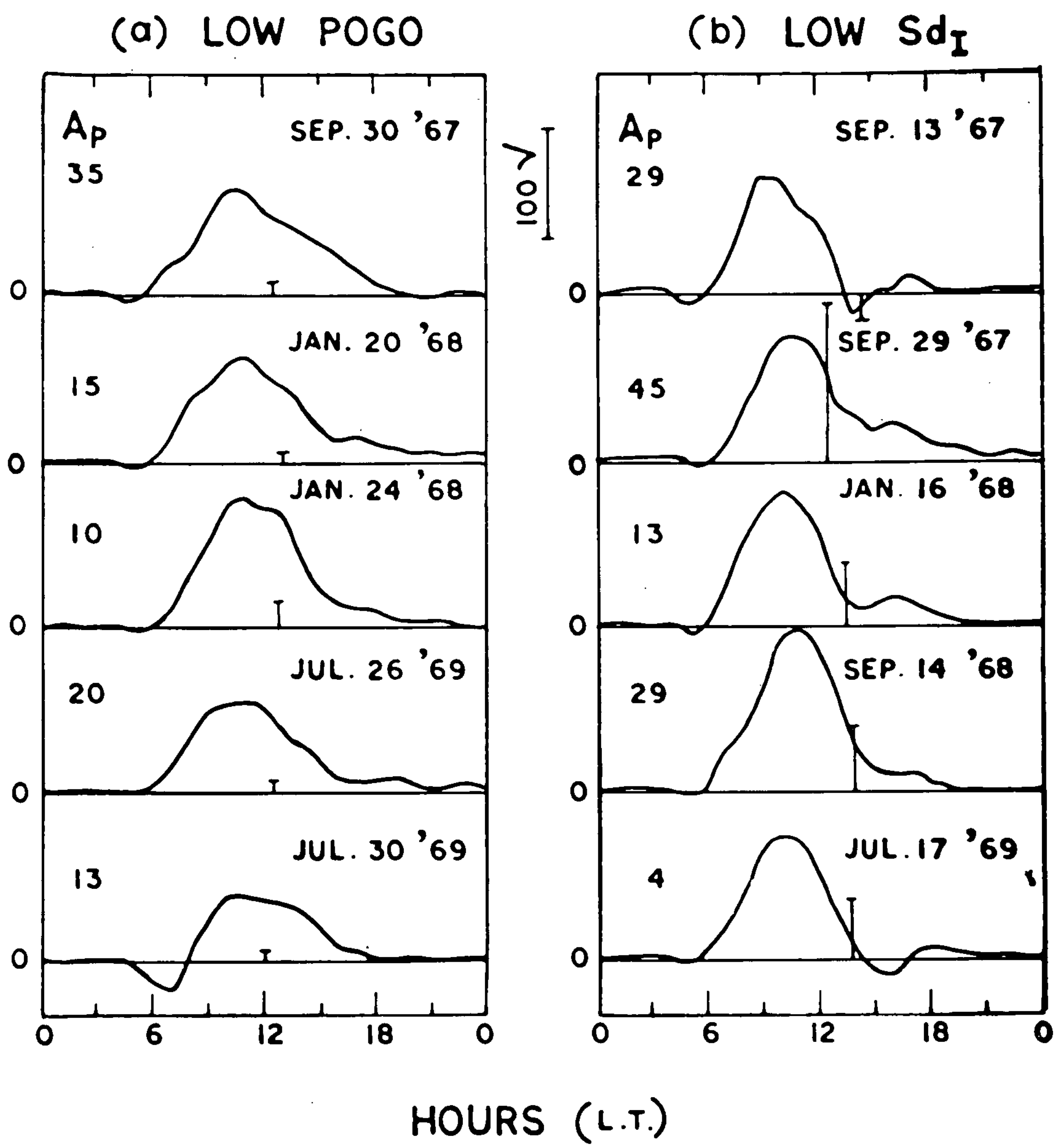

Figure 2. Sample plots of diurnal patterns of ΔSd_I for a few selected dates when equivalent POGO amplitudes were (a) smaller than ΔSd_I and (b) greater than ΔSd_I. POGO amplitudes are shown as vertical bars of appropriate heights at appropriates POGO traverse times (L. T.).

However, it is shown that the day-to-day changes in the daily variation amplitudes at Alibag and Trivandrum do not correlate very well (Kane, 1971). The correlation is no doubt positive but only about +0.4. Hence the difference Sd_{I}=H(TRI)-H(ALI)+Sq(ALI) may have some errors due to the non-correlative part. We expect this to be of the order of about 20 gamma in extreme cases. However, even a vertical error bar of this magnitude will not make the points in Figure 1 look any better aligned on a straight line in every case.

Another possibility is that the electrojet may not be the only source of the geomagnetic changes. If there are other current systems in the plasmasphere as also in the magnetopause and magnetospheric tail, these will have an altitude dependence but the POGO altitude is only about 600 km and is so near to the earth that it is doubtful whether any of the above current systems will produce substantially different effects at ground and at 600 km altitude. On the other hand, if there are other current systems in the ionospheric F2 region (and above) which have remained undetected so far, these may produce divergences between ground and POGO observations. The problem of the counter electrojet itself is quite intriguing. The present analysis shows that there is a definite counter electrojet effect observed at POGO altitudes also. It will also be interesting to see the role played by vertical current (Untiedt, 1967; Sugiura and Poros, 1969), if any, that may be operative in the equatorial region.

Thanks are due to Prof. J.C. Cain for supplying the data for POGO traverses, to the Director of Colaba and Alibag observatories for the magnetic data and to the Department of Space, Government of India, for financial support.

THE ELECTROJET FIELD FROM SATELLITE AND SURFACE OBSERVATIONS IN THE INDIAN EQUATORIAL REGION

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The amplitudes of jet signature, ΔF, from POGO observations over the Indian equatorial zone from 60° to 95°E are compared with ΔH at the two equatorial stations, Trivandrum and Annamalainagar, and Alibag, which is outside the electrojet. The comparison is restricted to fairly quiet days defined by $A_p<10$. ΔH is the excess field at the local time of dip-equatorial passage of the satellites over the field averaged at four pre-dawn hours. First ΔF, standardized to the height of 400km (Cain and Sweeney, 1972), is compared with ΔH_{TR} and also with $\Delta H_{TR} - \Delta H_{AL}$. This comparison is shown in Figure 1a, b. Omitting days for which the subjective uncertainty in ΔF exceeded 5γ, 49 days were available for comparison. In both the plots, a linear relationship is observed but with a considerable scatter. The correlation coefficients between ΔF (400 km) and ΔH_{TR} and between ΔF (400km) and $\Delta H_{TR} - \Delta H_{AL}$ are +0.79 and +0.86 respectively. The regression lines, indicated as dashed lines in Figure 1a and b, for the two pairs of data have the equations:

$$\Delta F \text{ (400 km)} = 0.22\, \Delta H_{TR} + 3.0$$

$$\Delta F \text{ (400 km)} = 0.30\, (\Delta H_{TR} - \Delta H_{AL}) + 1.1$$

In order to examine if the magnitudes agree, a further comparison was made. Surface electrojet fields were extrapolated to satellite heights above the axis of the electrojet assuming a simple model of a band current of width 2W, located at a height of 100 km with its image current at 500 km below the surface of the earth. Following Yacob (1966), values of W were derived using ΔH at the three observatories. Days with abnormally low derived values of W (less than 50 km) were omitted, leaving 50 days for comparison, including those for which the subjective uncertainty in ΔF was greater than 5γ. The results are shown in Figure 2a, where the line of equality has also been drawn. While a majority of points are fairly close to the line of equality, a good number of them show large departures, particularly in the lower magnitude range, ΔF being generally smaller. ΔH, standardized to a height of 400 km using the computed values of W as well as with W uniformly taken equal to 225 km (Cain and Sweeney, 1972) are plotted against ΔF (400 km) in Figure 2b and c. The comparison in these two cases shows that the relationship is less satisfactory, ΔH being too large in most cases.

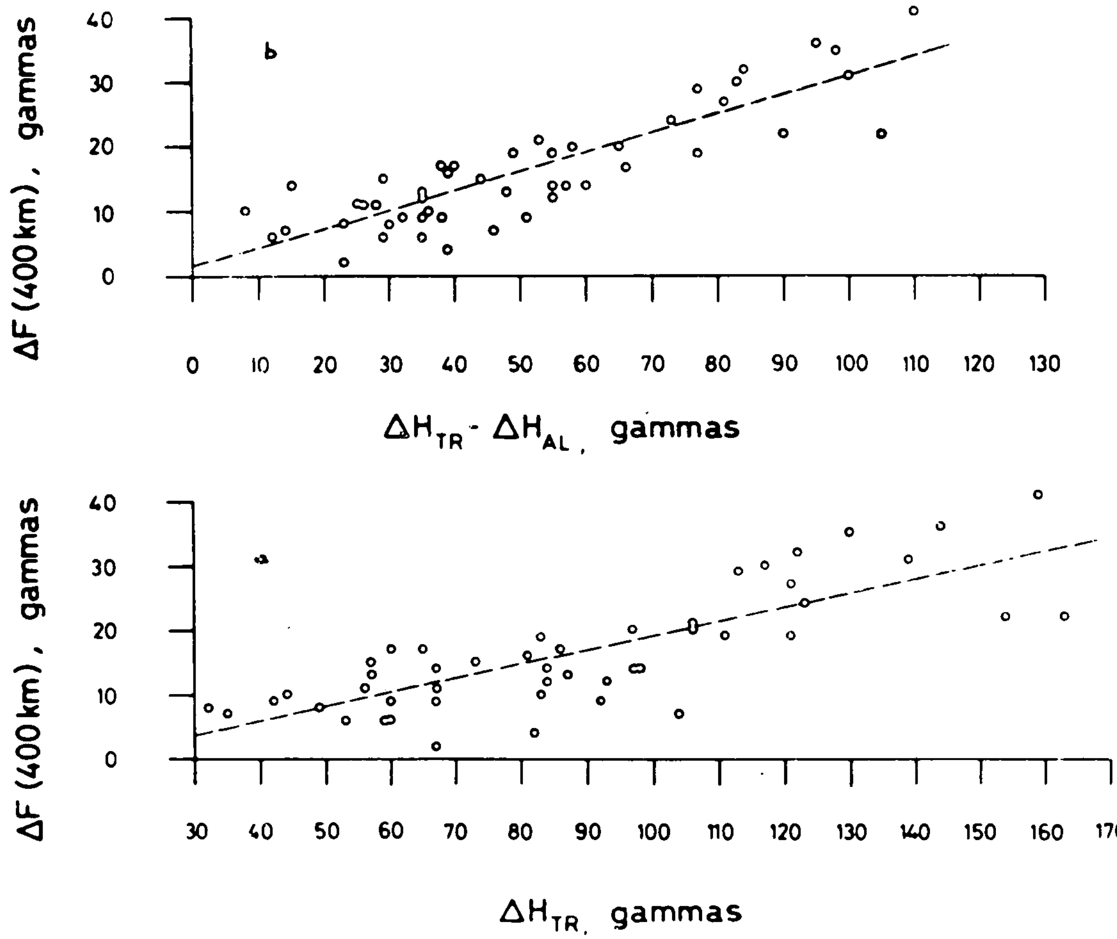

Figure 1. Correspondence between amplitudes of jet signature from POGO observations, ΔF (400 km), and the field at Trivandrum, ΔH_{TR}, (a) and between ΔF (400 km) and the field difference at Trivandrum and Alibag, $\Delta H_{TR} - \Delta H_{AL}$, (b).

The large scatter seen in Figure 1a and b may be ascribed to latitudinal shifts in the position of the electrojet as well as to differing instants of time to which ΔH and ΔF correspond, the longitudes of the stations and those of dip equator crossings of the satellites being different. The main cause of inequality between ΔH and ΔF in Figure 2a, b and c appears to be due to the contribution of the induced currents since these currents augment the northward surface field but diminish the southward field at satellite heights above the electrojet.

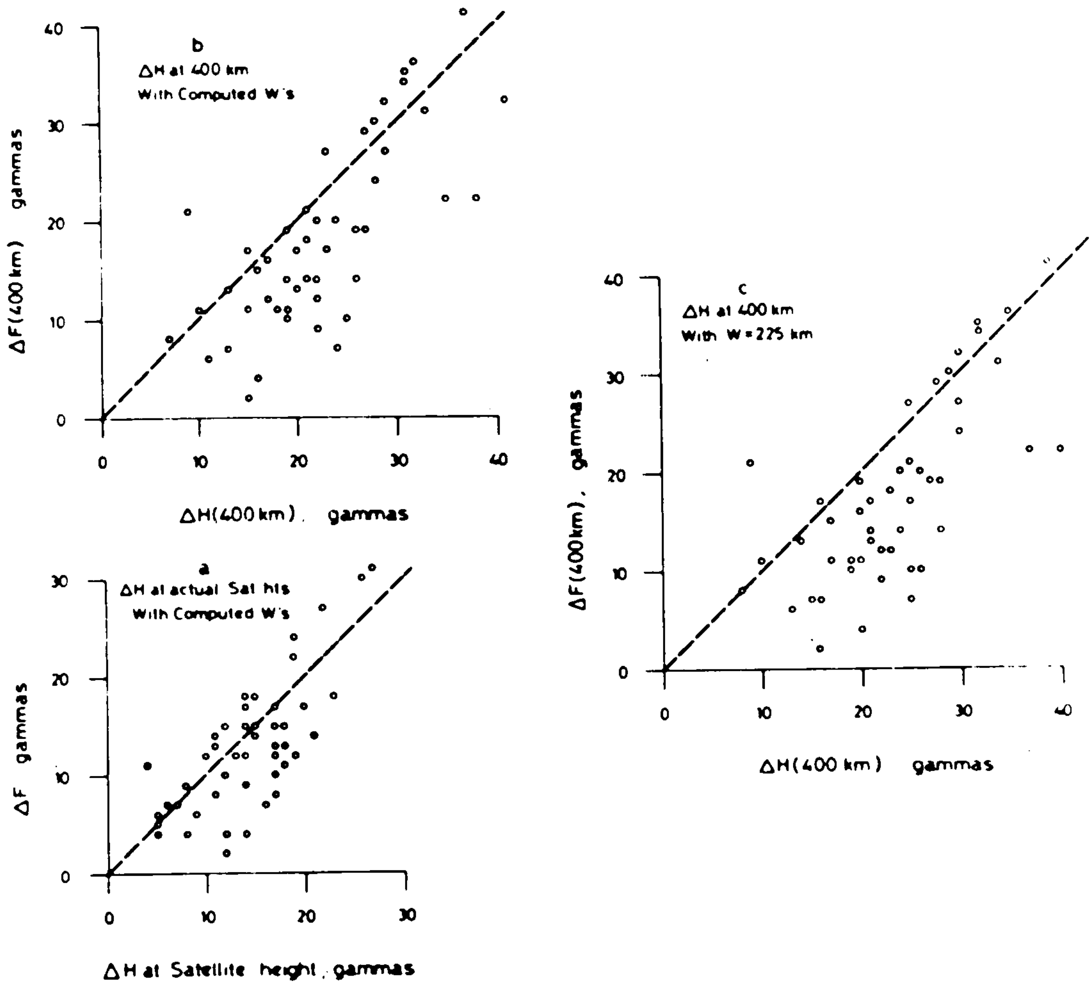

Figure 2. Comparison of amplitudes, ΔF, of jet signature from POGO observations and the ground-based jet fields, ΔH, extrapolated to satellite heights.

Our grateful thanks are due to Dr. J. C. Cain for supplying us the POGO data pertaining to the Indian Equatorial Zone and for his encouragement in undertaking the comparison.

CORRELATION OF SATELLITE ESTIMATES OF THE EQUATORIAL ELECTROJET INTENSITY WITH GROUND OBSERVATIONS AT ADDIS ABABA

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ABSTRACT

Of the 2000 OGO-4 and OGO-6 equatorial passes, 112 were within 10° either side of Addis Ababa. Twenty five passes happened during magnetically quiet periods when the index $a_p \leq 4$. Correlations were sought between the effect of the equatorial electrojet at satellite altitude and ground measurements. When the ground values $\Delta \dot{H}$ (AA) were read at the L. T. corresponding to the local time at the longitude of the satellite, the correlation is very good for 80% of the observations. The inverse slope of the ground effect versus satellite effect is about 3. 8 for Addis Ababa. A ΔH (AA) threshold of about 40 gammas was found below which the satellites did not register any electrojet effect. Some observations with excessive residuals correspond to H (AA) traces of irregular shapes; others'cannot be explained unless one postulates the existence of non-electrojet ionospheric currents which distort the magnetic field at satellite height much more than at the surface of the Earth.

INTRODUCTION

The equatorial electrojet (EEJ) is a well established geomagnetic phenomenon which was detected on surface magnetograms, first at Huancayo in 1922 and then at other longitudes along the dip equator. The main cause of the electrojet was inferred to be a high intensity ionospheric current located in the E layer at about 110 km above the earth's surface. The vertical structure and horizontal irregularities of the E layer were then investigated by rocket probes and radar techniques especially in Peru and India. Unfortunately, these ionospheric experiments have been performed at even fewer sites than the ground-based measurements.

With the launching of the POGO satellite series, continuous meridional profiles of the geomagnetic field were obtained during the period 1967-1970. When these profiles were compared with a reference model, the residuals show various anomalies. One of these anomalies is a negative trough repeatedly appearing over the earth's dip equator during day-time hours. This negative V-shape anomaly on the satellite records has been identified as the "signature of the equatorial electrojet" (Cain and Sweeney, 1972).

OGO-4 and OGO-6 observations were made available at the Symposium on Equatorial Aeronomy at Ibadan (Cain and Sweeney, 1972). The problem we are now faced with is to see if there is any correlation between the amplitude of the EEJ effect registered by POGO satellites and the magnetic traces recorded at ground stations located near the dip equator. Addis Ababa (AA) is one of these few equatorial stations at dip latitude -0.5°.

From the start, one should not expect a perfect one-to-one correlation between all satellite and surface observations as though the EEJ were an isolated phenomenon that magnetometers could single out. Satellite and surface magnetometers register the integrated effect of several fields from different environments: the satellite looks downwards at the EEJ through 300-700 km of ionospheric environment while the surface magnetometer looks at the same EEJ from some 100 km below through some 20 km of ionospheric thickness. It is assumed that the highest contribution to the equatorial magnetic field comes from the eastward ionospheric current flowing through the E layer; there are however, non-electrojet fields of magnetospheric and upper ionospheric origin, which to a certain extent influence the observed field. These non-EEJ fields certainly have more influence at satellite altitudes than at the surface of the earth.

The ideal set of observations for a comparison between satellite and ground-based measurements would be overhead passes when the only difference between satellite and station traces could be attributed to location of the sensors in different environments. Unfortunately, only about 1 in 1000 OGO-4 and OGO-6 day-time traversals over the dip equator is over an equatorial station. Out of 2000 passes, only 2 were over Addis Ababa (nos. 55 and 56 of the 112 events chosen for study). Other passes had therefore to be selected; Table 1 indicates the total number of passes within certain ranges of longitude with respect to Addis Ababa (Longitude: E38.8°).

Table 1

POGO Passes over AA

Total Number of Passes	Location in Longitude
2	Practically overhead $\leq 0.1°$
10	within $\pm 0.5°$
13	within $\pm 1.0°$
51	within $\pm 5.0°$
112	within $\pm 10.0°$

A difference in longitude between satellite and ground station effectively means a difference in local time (LT) between two simultaneous observations. The facts, (a) that rapid magnetic variations are simultaneous at all longitudes and are therefore Universal Time (UT) dependent, (b) that the day-to-day equatorial enhancement of all magnetic variations is L. T. dependent, and (c) that the intensity of the EEJ is not constant at all longitudes, restricts the selection of useful passes to those occurring during very quiet magnetic conditions and within a limited distance from the ground station. To meet these requirements, in the present paper, the upper limit of magnetic activity was set at $a_p \leq 4$ and the maximum distance from AA at $\pm 10°$ of longitude. Of the original 112 passes, only 25 meet these requirements. For reference, Table 2 indicates:

(a) the parameters of each selected POGO pass

(b) the indices of magnetic activity at the time of observation

(c) the "estimated amplitude" of the EEJ signature reduced to a satellite altitude of 400 km (after Cain and Sweeney, 1972)

(d) the amplitudes of the Sq (H) trace above night-time level at Addis Ababa (AA) and their deviations from the best fit mean regression line

'UT' indicates ΔH amplitude at AA at the same UT as the satellite observation

'LT' indicates ΔH amplitude at AA corresponding to the L. T. of observation at POGO location

(e) passes which were rejected in the computation of the least squares fit

(1 and 2 refer to UT and LT computations, respectively)

(f) "final" residuals (explained in the text)

In comparing the maximum amplitude (Sy) of the EEJ signature with ΔH at a ground station, one implicitly assumes that the ground station lies under the center of the EEJ at every pass, which is certainly not the case. Therefore, in certain cases, a latitude correction should be considered.

Table 2

Selected POGO Passes Near Addis Ababa

Passes						Activity Indices					Sy		ΔH (AA)					
″	DATE	UT	LT	h	$\Delta\zeta^\circ$	C_i	K_p	A_p	a_p	Dst	S	P.E.	UT (1)	(O-C) R'	LT (2)	(O-C) R'	Rejected	R''
1	68. II. 06	0938	1119	440	-10.0	0.0	1^-	2	3	-19	24 ±	1	148	- 5.3	131	+ 0.3		< 1
4	67. IX. 26	1043	1250	510	- 9.4	0.2	3^-	4	2	4	6	5	78	- 3.6	91	- 7.2	2	2.2
10	69. VII. 22	1102	1259	413	- 8.0	0.4	1°	7	4	10	10	6	53	+ 7.4	69	+ 2.6		0
21	68. IX. 26	1017	1238	555	- 5.9	0.2	1°	4	4	17	26	1	141	- 1.3	146	- 1.7		< 1
24	68. IX. 30	0952	1216	603	- 5.5	0.4	0^+	7	2	22	15	1	114	- 4.7	115	- 4.5		3.5
29	68. X. 04	0926	1154	653	- 5.0	0.2	0^+	3	2	-16	23	1	128	- 0.7	132	- 1.0		0
30	68. II. 02	0840	1143	468	- 4.6	1.0	3°	19	3	-17	26	6	113	+ 7.6	146	- 1.7		0
31	69. VII. 17	1126	1338	444	- 4.5	0.1	1^-	4	3	9	26	1	89	+13.3	105	+ 9.1	1.2	8.1
33	68. X. 08	0859	1131	701	- 4.3	0.4	1°	7	4	3	21	2	118	0.1	121	- 0.1		1.9
37	69. X. 08	1237	1514	504	- 2.9	0.1	1^-	3	3	- 6	10	1	37	+12.0	38	+10.8		9.8
42	67. X. 13	0832	1115	726	- 1.9	0.8	1^-	9	3	-11	16	2	107	- 1.8	99	+ 0.7	1.2	1.3
43	67. X. 04	0924	1206	600	- 1.8	0.1	0^+	4	2	6	3	1	68	- 4.8	61	- 2.3		1.3
48	67. IX. 22	1032	1313	470	- 0.9	0.6	1°	10	4	-12	24	6	131	- 0.5	123	+ 2.4		0
57	68. IX. 25	0959	1244	543	+ 0.1	0.1	1^-	2	3	0	26	2	149	- 3.6	141	- 0.4		0
73	69. VIII. 11	0740	1027	511	+ 4.0	0.2	0^+	4	2	15	15	5	112	- 4.2	148	-13.2	2	8.2
74	68. II. 14	0754	1032	421	+ 4.4	0.2	1°	5	4	-16	27	3	130	+ 2.8	130	+ 3.5		< 1
84	68. IX. 20	1006	1312	491	+ 5.9	0.3	1^-	7	3	2	7	3	73	- 1.2	62	+ 1.4		0
86	68. IX. 24	0941	1249	532	+ 6.1	0.1	1^-	4	3	- 5	17	7	142	-10.6	114	- 2.3	1	0
89	67. X. 06	0841	1155	630	+ 6.4	0.2	1°	6	4	3	29	1	141	+ 1.7	126	+ 6.6	2	5.6
93	68. I. 25	0942	1232	557	+ 6.7	0.2	1^-	4	3	- 1	13	3	110	- 5.6	110	- 5.2		2.2
95	67. IX. 27	0932	1245	520	+ 6.8	0.1	1^-	5	3	11	12	5	113	- 7.4	87	- 0.1		0
102	69. VII. 29	0908	1205	409	+ 7.2	0.1	0^+	2	2	- 2	25	7	115	+ 5.0	122	+ 3.6	1	0
104	68. II. 27	0625	0917	493	+ 7.5	0.6	1°	8	4	4	20	6	97	+ 5.1	116	+ 0.2		0
111	69. X. 17	1038	1407	633	+ 9.3	0.4	1°	6	4	8	13	3	75	+ 4.2	76	+ 3.7		1
112	69. VIII. 01	0833	1142	421	+10.2	0.1	0^+	3	2	10	18	4	96	+ 3.3	106	+ 0.8		0

OVERHEAD PASSES

55	67. IX. 16	1104	1346	430	0.0	0.7	2^-	11	6	5	14	2	73	+11.8	71
56	68. IX. 09	1135	1413	423	0.0	0.8	2°	10	18	-19	10	3	82	- 0.7	79

Note: The identification numbers refer to the complete list of observations within 10° of AA.

ANALYSIS OF THE DATA

POGO RECORDS WITH CLEAR Sy SIGNATURES

In this paper, Sy refers to the "estimated amplitude" (AMP) of the equatorial electrojet signature reduced to a satellite height of 400 kilometers (Cain and Sweeney, 1972). ΔH (AA) is the amplitude of the S_q (H) trace above night level, either at U.T. or L.T. times in Addis Ababa. This reference night-time base-line was not calculated from the midnight mean hourly values as is usually done, because the midnight values at AA are often unrealistic due to the presence of two consecutive large amplitude bays which appear quite regularly around LT 2300. The night base-line was determined by drawing on each magnetogram a straight line between the two most level sections of the night traces preceding and following the observations. Automatically, the non-cyclic variation is eliminated.

The best-fit regression lines were computed on the assumption that the ordinates and abscissae values were equally well determined.

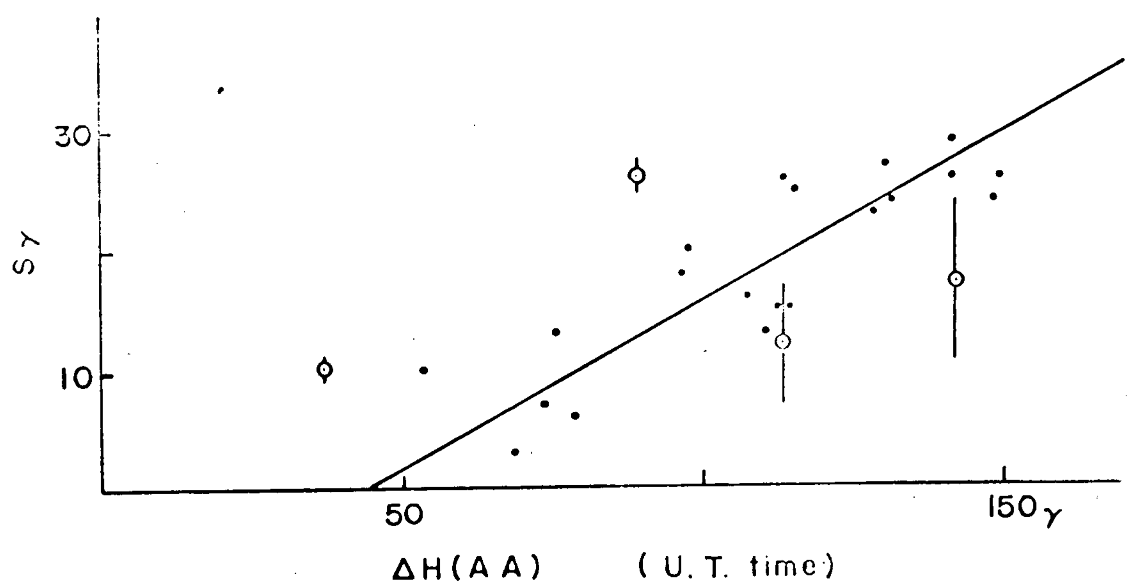

Figure 1. Correlation of the amplitude (Sy) of the electrojet signatures with the simultaneous values of ΔH at the ground station AA. The circled dots (⊙) indicate anomalous values.

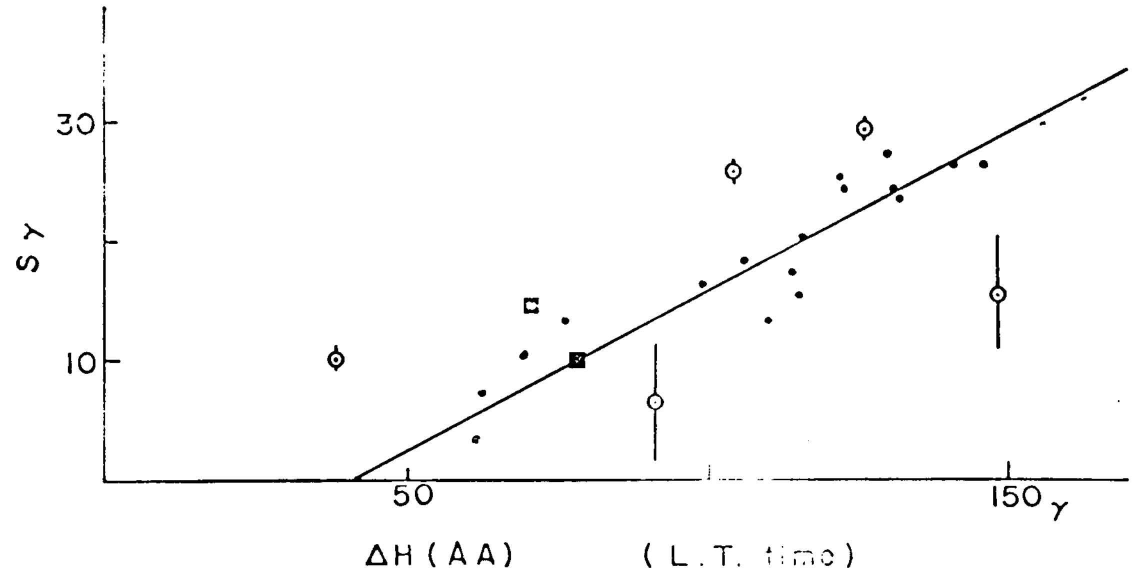

Figure 2. Correlation of the amplitude (Sy) of the electrojet signatures with the ΔH (AA) values at the L. T. in Addis Ababa corresponding to the local time at the satellite. The square dots (⊡) indicate overhead passes.

Figures 1 and 2 show the scatter diagrams of the 25 selected Sy observations during very quiet days ($a_p \leq 4, \Delta° \leq \pm 10°$) plotted against ΔH (AA) at both simultaneous U. T. and corresponding L. T. times. In these figures some points, indicated by circled dots, depart abnormally from the mean curves; the regression lines were then re-calculated without these points and error bars were added to show their P. E. (Cain and Sweeney, 1972). The difference in the slope is negligible (see Table 3). In Figure 1, the outliers below the regression line (observations 86 and 95) would fall within the confidence limits if their P. E. were considered; the 2 others located above the regression line (observations 31 and 37) are certainly anomalous. In Figure 2, only one rejected point (observation 95) could fall within the confidence limit.

In both cases, when the points of excessive variance residuals are eliminated, the correlation is good. The inverse slopes Δx/Δy in Figures 1 and 2 are 3.6 and 3.8 respectively and the regression lines intercept the x-axis at ΔH (AA) = 44 and 41 gammas respectively. Note that when the observations are not restricted to very low magnetic activity, the inverse slope increases proportionally.

Table 3 summarizes some important aspects of these 2 graphs:

Table 3

Characteristics of the Regression Lines					
Figures	N	a	b	$\Delta x/\Delta y$	$\Delta H_{y=o}$
1 UT	25	-9.6 ± 3.9	0.26 ± 0.04	3.86	38
	21	-12.3 ± 3.5	0.28 ± 0.03	3.55	44
2 LT	25	-16.9 ± 4.1	0.26 ± 0.04	3.85	39
	20	-10.8 ± 2.3	0.26 ± 0.02	3.81	41

N = number of observations

a, b = factors in equation $Sy = a + b\ (\Delta H)$

$\Delta x/\Delta y$ = inverse slopes

$\Delta H_{y=o}$ = regression line intercept on ΔH (AA) axis

It is of interest to note:

(1) That the inverse slopes are practically the same in the two graphs (about 3.8). It was found that $\Delta x/\Delta y$ increases rapidly for greater magnetic activity; it reaches 6 at AA for $a_p \leq 7$.

(2) When the outliers showing abnormal variance residuals are rejected, the s.d. is higher in Figure 1 than in Figure 2. This is to be expected because the amplitude of the electrojet enhancement at the same U.T. varies with longitude. For this reason, the range of longitude was limited to 10° either side of AA. In Figure 2, the scatter of most of the points has been reduced but the anomalous points have even greater deviations than in Figure 1.

(3) The x-intercepts of the regression lines indicate a minimum of ΔH(AA) $= 40$ gammas below which no EEJ signature appears at satellite heights. This ΔH threshold above night level is probably the equivalent of the non-electrojet contribution to the equatorial H-field which other authors (Osborne, 1964; Onwumechilli, 1967; etc. . . .) attempted to determine by extrapolation from observations at sites near but outside the electrojet influence.

VARIANCE RESIDUALS ON THE L. T. GRAPH (FIGURE 2)

On the L. T. graph, 5 points were rejected in the computation of the regression line because of their excessive residuals. In order to explain these residuals independently of magnetic activity, because all the rejected observations were made when $C_i \leq 0.2$ and $a_p \leq 4$, the residuals were plotted first against the longitude and then against the altitude of the satellites. It was found that there is no longitude dependence for the residuals; the five discarded points are distributed at random. In comparison, 3 of the 4 anomalous points are located between 500-510 kilometers suggesting a possible non-electrojet influence at that altitude.

The satellite magnetometer measures the total field F; the appropriate reference for comparison of Sy with ground records should be ΔF. If the ground station is situated at the dip equator, $\Delta F = \Delta H$. A shift in latitude of the electrojet would therefore mean a change in ΔF. For that reason, it was thought worthwhile to re-plot Sy vs ΔF (AA) L. T. However, it was found that the inverse slope as well as the s. d. were exactly the same for Sy vs ΔF (AA) L. T. as for Sy vs ΔH (AA) L. T.; the same points also anomalously depart from the normal curve.

In conclusion, if the probable errors (P. E.) in Sy are taken into consideration and subtracted from the residuals in Figure 2, we obtain "final" residuals (R' in Table 2):

20	are ≤ 2.2 gammas
5	range between 3.5 and 9.8 gammas

Residuals of ± 2.2 gammas are within the accuracy of evaluating ΔH on magnetograms. The final residuals ≥ 3.5 gammas are much larger than the combined probable errors of Sy and ground measurements. It is concluded that 80% of the observations correlate well but that five show significant departures. If observation 24 (R' = 3.5) is neglected because of a Dst value of +22 gammas, we are left with 4 observations for which R' ≥ 5.6 gammas. Such residuals cannot be explained unless one postulates the presence, in the very near vicinity of the space craft at about 500 km, of ionospheric currents which could produce at that altitude a magnetic field as high as that of the electrojet (see observation 37 where R' = 9.8 as compared with Sy = 10 ± 1 gammas).

POGO RECORD WITHOUT ELECTROJET SIGNATURES

Of the 112 POGO traversals near Addis Ababa, 11 showed 'NO ELECTROJET' effects. They are listed in Table 4 with the corresponding indices of geomagnetic activity and amplitudes of the H trace.

Table 4

NO Sy Observations								
	Magnetic Activity					ΔH (AA)		
Observation	C_i	K_p	A_p	a_p	Dst	UT	LT	Max.
3	0.2	0^+	4	2	0	117	92	124
44	0.6	2^o	8	7	4	48	36	79_s
52	0.3	1^-	5	3	15	73	69	104
62	0.6	3^-	10	12	-15	D	D	83_s
65	0.3	1^+	5	5	7	45	45	80_s
67	0.2	2^-	6	5	7	33	23	186
77	0.6	1^-	8	3		42	40	79
85	1.4	6^-	48	67	-65	-23	-20	D
94	0.7	0^+	9	2	2	27	20	93
100	0.3	2^o	5	7		38	23	119
108	0.8	1^+	6	18	11	33	9	D

D = too much disturbed for any good evaluation

s = from smoothed H-trace

Max = maximum ΔH value of the day

Of these eleven, nine occurred when the H trace was below or just above the 40 gamma threshold, either because the H trace was strongly disturbed or because the observations took place in late afternoon. For the remaining 2 observations, nos. 3 and 52, an Sy minimum of 12 and 7 gammas respectively is expected. In both cases, the magnetic activity was very low ($a_p \leq 3$); on these days it was observed that the morning increase of the H trace was normal up to local noon but that the afternoon slope did not attain its night-time value until late in the night, as illustrated in the sketch of Figure 3B. Such traces are of normal occurrence at AA (Gouin, 1963). What happens to the electrojet current in the afternoon in such cases remains to be explained.

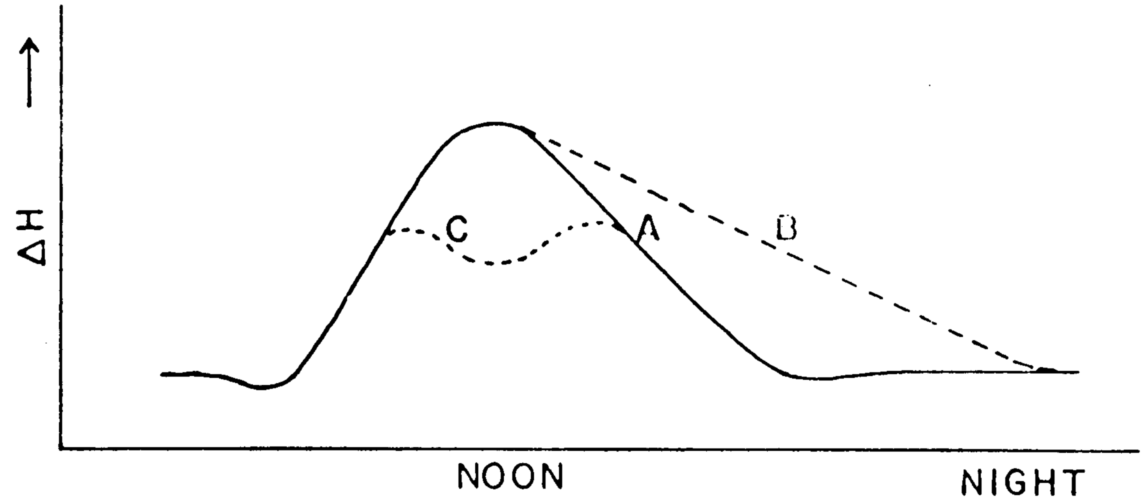

Figure 3. Typical S_q (H) equatorial curves. (A) is the normal S_q (H) traces; (B) refers to those traces when the afternoon slope does not reach the night level before late at night; (C) is a typical "counter-electrojet" curve with a minimum at local noon.

POGO RECORDS WITH ELECTROJET SIGNATURES "TOO BROAD" TO BE EVALUATED

Table 5 lists 10 observations catalogued as "Too Broad" by Cain and Sweeney (1972). Seven occurred either during disturbed days or when the H trace was below the ΔH (AA) = 40 gamma threshold.

There remain 3 observations, namely nos. 68, 81 and 101, to consider:

(1) During observations 68 and 101 the S_q (H) traces were very regular and undisturbed. From the surface magnetograms, there is no reason to suspect that the EEJ could be abnormal.

(2) Observation 81 is most interesting because it touches the controversial issue of the "counter electrojet" (Gouin and Mayaud, 1967). The S_q (H) trace on that day showed a minimum at noon time and an afternoon maximum at LT 1435 (as illustrated in Gouin, 1962, Figure 1B). On such days, the Esq has also been observed to disappear on equatorial ionograms (Fambitakoye, Rastogi, Tabbagh and Vila, 1973).

Table 5

"Too Broad" Sy Observations								
	Magnetic Activity					ΔH (AA)		
Observation	C_i	K_p	A_p	a_p	Dst	UT	LT	Max.
9	1.2	4^-	21	15	-13	-21	-6	80_s
23	0.9	3^+	14	18		72	78_s	102_s
32	0.2	1^o	5	4	-11	27	24	118
45	0.5	3^o	10	15	-11	68	61	88
68	0.2	1^o	5	4		63	68	109
69	0.9	3^o	15	16	-16	24	14	122
71	1.2	2^+	25	32	7	37	38	80_s
81	0.2	1^-	4	3		50	56	65
92	1.3	5	35	39	-25	Very disturbed		
101	0.6	2^o	6	7	0	73	72	143

CONCLUSIONS

There is a fundamental correlation between the equatorial electrojet signature at satellite elevations and the magnitude of the S_q (H, F) traces as seen at equatorial ground stations. The correlation is better if either the ΔH or ΔF ground values are taken at the local time corresponding to the local time at the longitude of the satellite.

There are clear-cut cases, however, where the Sy amplitudes anomalously depart from the normal. Some of these anomalies coincide with abnormally shaped H traces; others occurred when the S_q (H, F) trace is absolutely normal at ground level. The presence of non-electrojet currents at satellite elevations, perhaps at about 500 km, could possibly be responsible for these anomalies. For the two overhead passes, if the only field source were the electrojet, one would expect proportional responses at the satellite and ground station, even for magnetically disturbed days. That the observation from one of these passes departs considerably from the normal correlation tends to confirm this hypothesis.

COMPARISONS OVER CENTRAL AFRICA

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Another paper, to be published (Fambitakoye, et al., 1973), discusses one aspect of the results from a chain of magnetometers operating in central Africa. The results from this network were analyzed to obtain the effect of the electrojet enhancement over and above the Sq(H) for the narrow region (< 1000 km) on each side of the dip equator. A series of 14 simultaneous observations were compared for the period 28 July - 13 August 1969 when the local time of the spacecraft was between 10 - 12^h and its altitude from 409 to 538 km. Using the values given by Cain and Sweeney (1972) for their estimated electrojet amplitudes, a scatter diagram was drawn against the surface amplitude reductions. A straight line fit to this curve was $\Delta H = 2.9\ \Delta F + 0.1$ with a scatter of some 10γ in ΔH.

The result of this short comparison indicates that there is a fair correlation between the satellite and surface variations and that the satellite amplitude is about a third of that observed at the ground.

ON THE CORRELATION OF THE GROUND DATA AT IBADAN WITH POGO SATELLITE RESULTS

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ABSTRACT

POGO satellite data are compared with the ground data at Ibadan. Results show poor correlation. The ratio Ground/POGO obtained from the scatter diagrams and extrapolated to the value on the jet axis is compared with other ratios from India, Addis Ababa and Huancayo. The variation in the ratios from different zones is discussed in the light of the results of the preliminary work on the upper mantle conductivity structure in Nigeria. It is concluded that the conventional model of image plane approximation used by Chapman and others in deducing the induction part of the electrojet is unrealistic in the face of recent results of Solid Earth Physics study.

INTRODUCTION

Many attempts have been made in the past to fit surface data to fields produced by various types of ionospheric current systems in low latitudes: - line currents, uniform band, band with a parabolic current distribution, Chapman (1951). Onwumechilli (1967) has used another function which allows for the change of the shape of a symmetric current from that of a near parabolic or gaussian distribution, to one where there is a possibility of a westward current outside the main positive eastward one. Other possible current models had been derived by Untiedt (1967) and by Sugiura and Poros (1969). The influence of the induction currents of the electrojet current system on the satellite and surface observations has not been addressed in a serious and realistic manner. Different authors who had considered the problem followed Chapman's lead in estimating the induction effect by the use of a model current system in the ionosphere to represent the electrojet, and the use of an infinitely conducting layer at some depth to estimate its induction effect. All the methods used so far by Forbush and Casaverde (1961), Onwumechilli and Ogbuehi (1967), Fambitakoye et al. (1972), and Osborne (pg. 59) follow the same pattern. There is an overwhelming evidence from solid earth physics study (seismic and induction) that there are low resistivity layers at crustal or subcrustal depth in various regions of the earth. Such reports of inhomogeneity in conductivity at shallow depths have been made by Adam for the Carpathian Basin (1970), by Dowling for Wisconsin (1970), by Mitchell and Landisman for Texas (1971), by Oni and Alabi for Nigeria (1972) by Hermance and Grillot for Iceland (1970) and by Berdichevskij and co-workers for Yakutia (1969). A more realistic approach to the effect of induction when comparing satellite and ground data is now overdue. In this paper, the author has compared the POGO satellite data (Cain and Sweeney, 1972) with the ground data at Ibadan. The results are discussed in the light of the solid earth study that had been carried out by the author in Nigeria.

METHOD OF COMPARISON

The method adopted here is a very simple one. The total field F(t) vector and H(t) vector corresponding to the POGO U. T. passes were computed for Ibadan. The difference between the local time and U. T. time at Ibadan is small - about one hour. Ibadan is not on the axis of the dip equator but Zaria is very near the axis. The average scaling factor for the magnitude of ΔH at Ibadan is 1.5. This factor was obtained from nine simultaneous records of ΔH at Ibadan and Zaria during the solar minimum of 1966. Hence in order to extrapolate the ground data at Ibadan to the magnitude on the electrojet axis, it is sufficient to multiply all ground values by 1.5. Since this is a constant factor, the Ibadan ground data had been plotted without extrapolation to the value on the axis. The POGO data are compared with the Ibadan ground data for all quiet days as indicated by studying the individual records at Ibadan. All POGO passes which correspond to slightly disturbed days on the Ibadan records are excluded in order to omit current sources from magnetospheric disturbances. Figure 1 shows the scatter diagram of the POGO results plotted against the horizontal field change ΔH at Ibadan for corresponding U. T. POGO passes. There is hardly any correlation. Figure 2 shows the average points calculated from this scatter diagram. Similar diagrams were constructed using the total field vector F(t) in place of the horizontal component. However, the results were essentially identical. The slope of Figure 2 was taken and multiplied by a factor of 1.5 to reduce to jet axis value, in order to compare with the results of others obtained by Gouin for Addis Ababa in East Africa, Kane for Trivandrum in India and Osborne for Huancayo (see other papers in this issue). Values of Ground/POGO at Ibadan and corrected as above are 3.5 from Figure 2 (and 3.2 from the total field comparison). Gouin obtained 4 for Addis Ababa in East Africa, Kane obtained values ranging from 5 to 8 for Trivandrum in India, Osborne obtained 4 for Huancayo in South America.

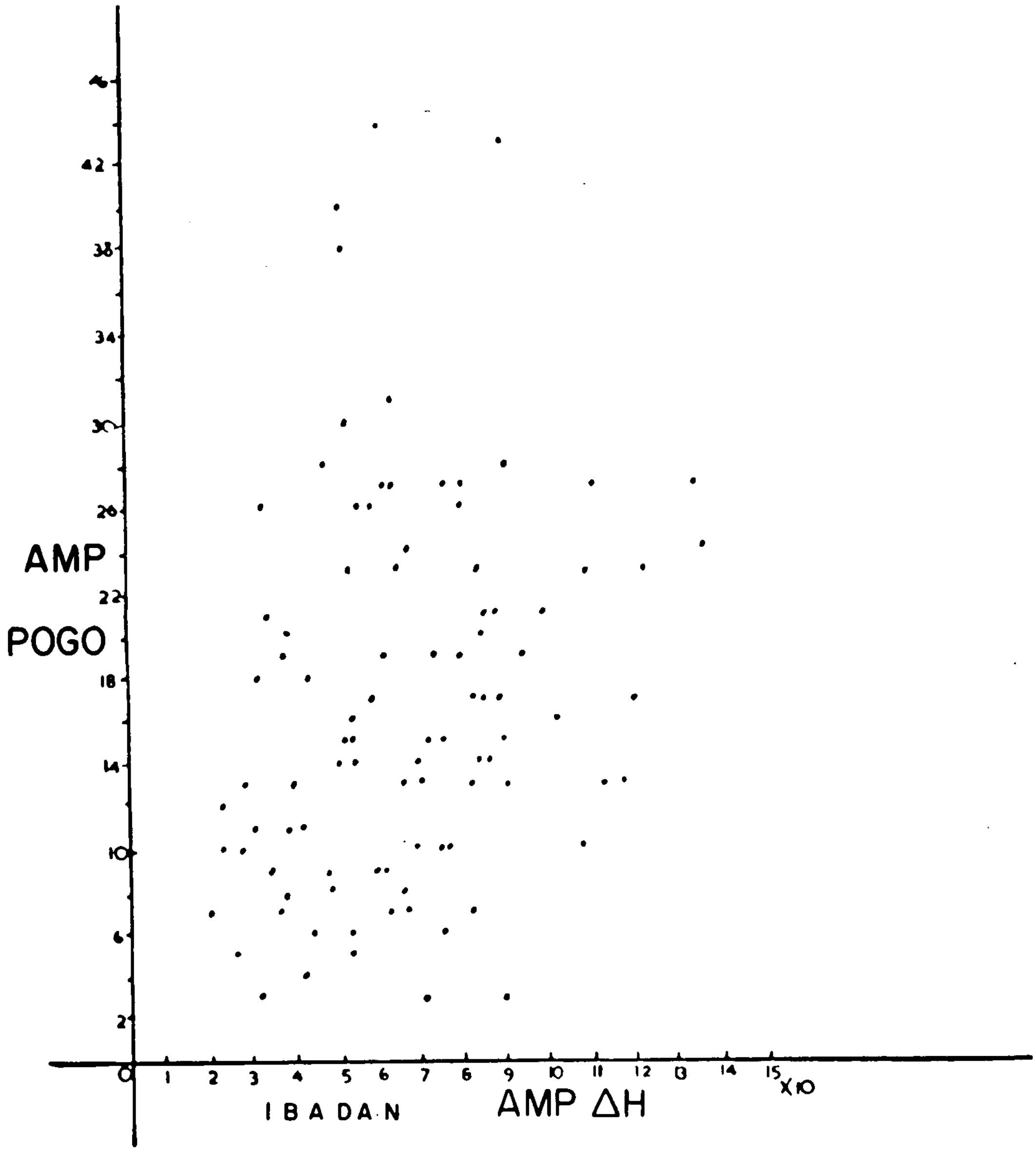

Figure 1. Scatter Diagram of POGO and the horizontal field component change ΔH at Ibadan.

DISCUSSION

The scattered values of the ratio Ground/POGO at the various stations are not surprising. The ratio is dependent on the complex finite conductivity structure of the earth at the different stations. Our work at Ibadan on the conductivity

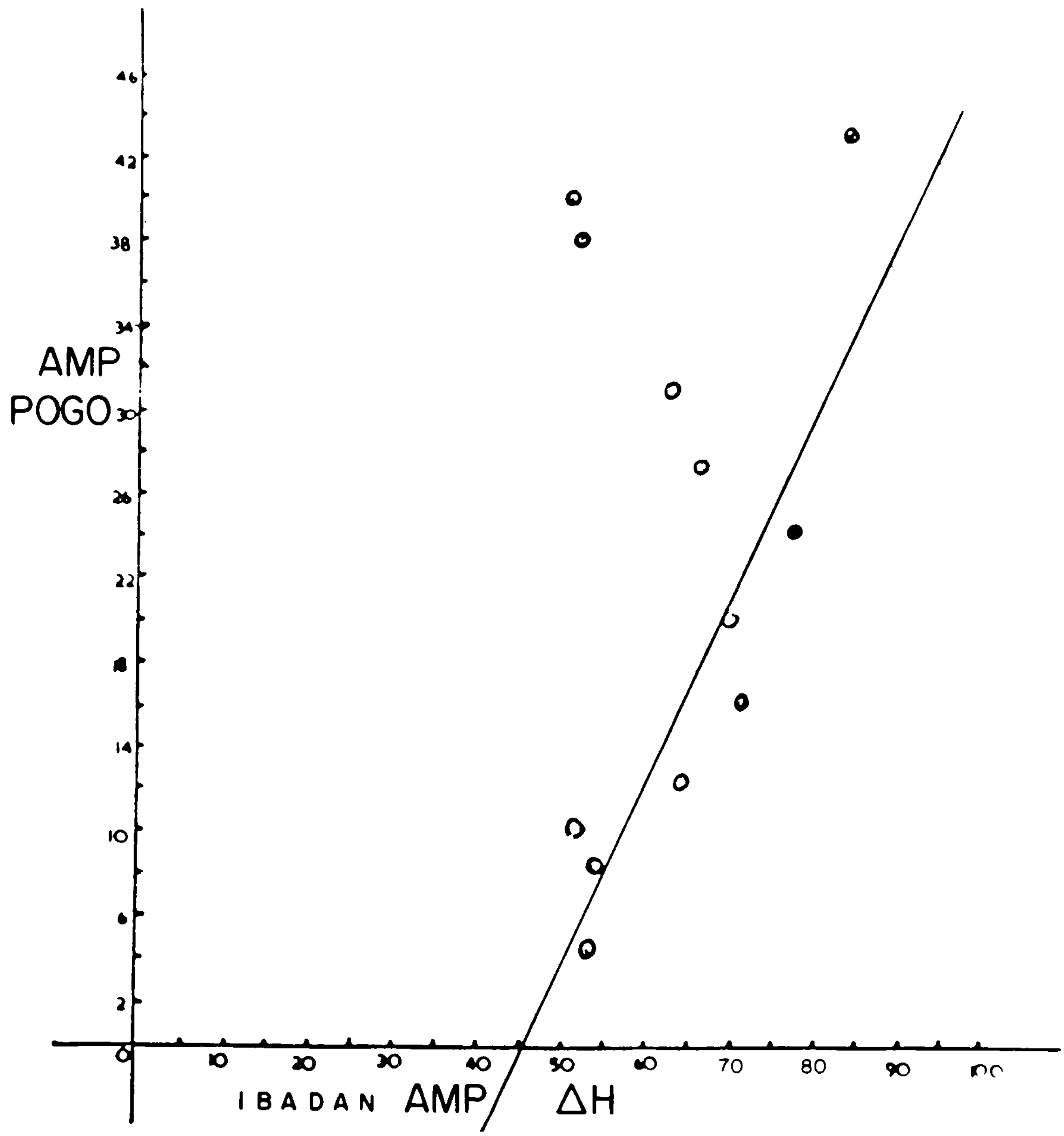

Figure 2. Average points calculated for ΔH scatter diagram.

structure of the earth in Nigeria (Oni and Alabi, 1972) revealed the relatively shallow depth of induction current for the electrojet. Figures 3 and 4 show the models used for the electrical conductivity of the subsurface structure at Ibadan, Kontagora and Zaria in Nigeria. Table 1 (taken from Oni and Alabi, 1972) also shows the relatively shallow skin depth for the narrow width of the electrojet, as compared with say worldwide sq. Hence the old technique of studying the induction effect of the electrojet by assuming an external ribbon current source

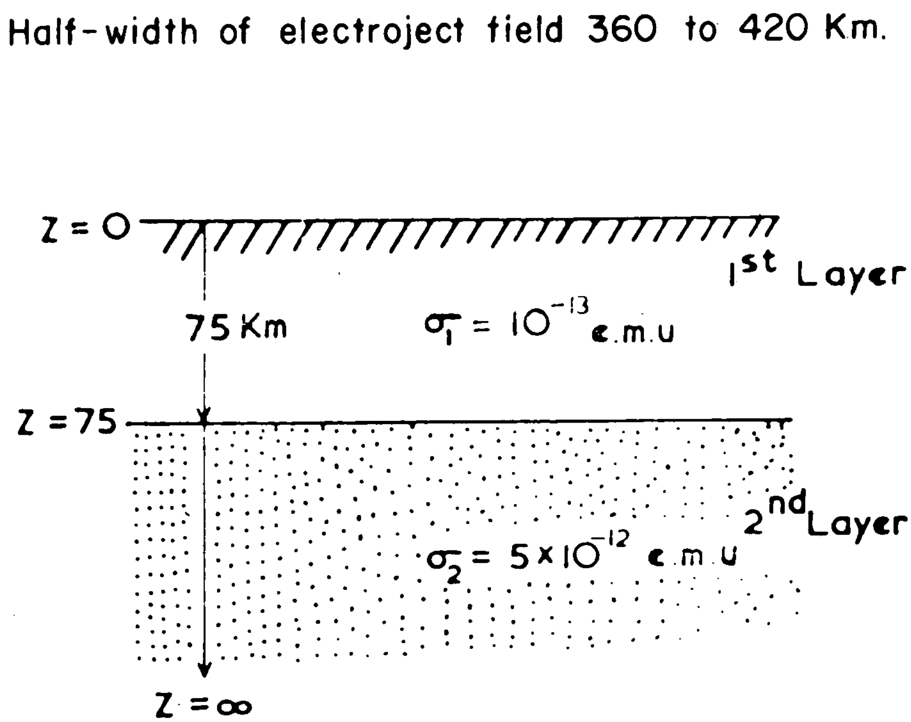

Figure 3. A model for the electrical conductivity of the subsurface structure at Ibadan (after Oni and Alabi, 1972).

and calculating the internal part from the image of such a ribbon at great depths is definitely unsuitable for the induction problem at low latitude. Fambitakoye (1972) from his work in Central Africa concluded that the electrojet has very little or no induced effects. Following Chapman's technique of estimating induction, Fambikatoye assumed an external source of half-width 300 kms in his model, height 105 kms, parabolic current density, and the internal induction effect is obtained from the image of such a ribbon at 600 km of depth. The existence of low resistivity layers at relatively shallow depths makes such earth models for the estimation of induction effect unrealistic. In the case of the induction effect of the electrojet, the narrower the source current, the shallower the skin depth; hence earth models of multilayers with finite conductivity at shallow depths represent a more realistic model for the estimate of induction effect of the electrojet. It is therefore not surprising that the Central Africa study which puts the induced current at 600 km of depth for a narrow external source current, yields negligible or non-existence of induction effect. At that

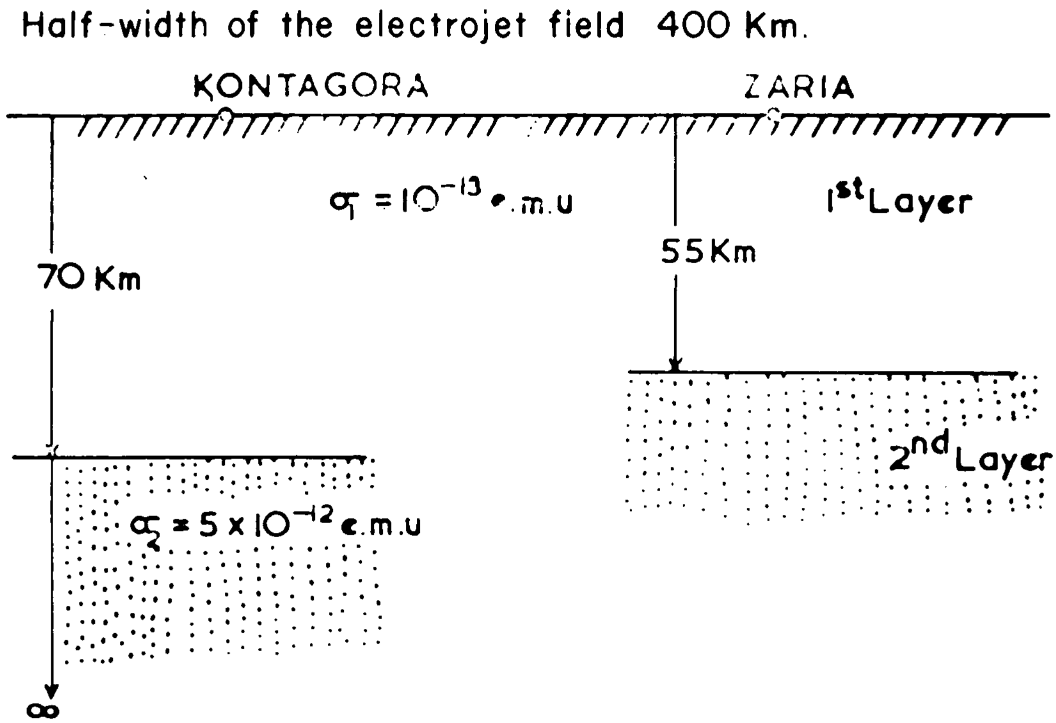

Figure 4. A model for the electrical conductivity of the subsurface structure at Zaria and Kontagora (after Oni and Alabi, 1972).

depth, from our study the electrojet source current with its relatively narrow width compared with the worldwide S_q, cannot produce any induced current. The very poor correlation between the POGO data and the ground data as shown by the scatter diagram of Figure 1 is due to the stronger contamination of the ground data by the induction of the electrojet in a relatively complex earth structure of finite conductivity, as compared with the satellite data. It is evident that to study the induction effect of the narrow electrojet, one must face the problem of studying the induction of multi-layered heterogeneous earth models of finite conductivity at shallow depths.

Using similar reasoning we also conclude that the Huancayo results of Osborne (this issue) could also be in error since he made a simple subtraction of the Sq effect by using the Pilar data.

Table 1

After Oni and Alabi, 1972

	24 hours	12 hours	8 hours
σ_1	10^{-13} e.m.u.	10^{-13} e.m.u.	10^{-13} e.m.u.
h	75 km	75 km	75 km
σ_2	5×10^{-12} e.m.u.	5×10^{-12} e.m.u.	5×10^{-12} e.m.u.
Half-width	420 km	360 km	360 km
Computed H_z/H_x	0.36	0.47	0.45
Observed H_z/H_x	0.37 ± 0.09	0.46 ± 0.11	0.43 ± 0.19
Skin depth	135 km	116 km	116 km.

CONCLUSION

While there is a great need for a worldwide comparison of low latitude ground data with satellite results, one of the most outstanding problems of correlation is the electromagnetic induction effect of the electrojet on the ground data. From the work we have carried out in Nigeria, it has become apparent that the electrojet, because of its narrow width, induces a current system in a relatively shallow depth, as compared with greater depths in non-electrojet areas of the world. Because of the possible variability and the heterogeneous nature of the relatively shallow conducting layers at many stations scattered all over the low latitude regions, it is not surprising that there is a poor correlation between the POGO satellite data and the ground data at Ibadan and at other stations like India, South America, and East Africa as evident from the papers presented at the fourth Equatorial aeronomy symposium. In addition, any variation in the widths of the electrojet from one zone to the other will be reflected in the skin depths.

ELECTROJET MEASUREMENTS FROM SATELLITE AND GROUND

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ABSTRACT

Comparisons between POGO electrojet profiles and the difference between the Sq variation at Huancayo less that at Pilar showed good correlation for 11 selected passes. The ratio of this surface enhancement of Sq due to the electrojet to the estimated amplitude at a mean satellite altitude of 500 km for these cases was 4.6 ±0.4. Similar ratios over India and the Philippines were for different satellite altitudes 7.1 ±.6 and 5.0 ±0.7 respectively. The width of the electrojet profile in the POGO data at Huancayo was interpreted in terms of the classical band current model with the resulting image depth of 625 ±100 km, current width of 520 ±50 km and average current intensity of 112 amp/km.

INTRODUCTION

The IAGA working group on the equatorial electrojet was supplied Difference Field plots of the OGO-4 profiles from the intervals September-October, 1967 and January-February, 1968 somewhat prior to the more comprehensive data summary of Cain and Sweeney (1972). The reference field used at that time was the POGO (10/68) internal field model (Cain and Cain, 1971). Although this model contained fewer harmonics and thus did not follow the main field as exactly as do later models, the electrojet signature shows up equally clearly in most cases and the measured amplitudes agree within 1-2γ of those given by Cain and Sweeney (1972).

VALUES FOR COMPARISON

For the first trial comparison two observatories in South America were chosen: Huancayo (nearly under the centre of the electrojet at 75° 20'W, 12° 03'S) and Pilar (away from the jet at 63°53'W, 31° 40'S). Satellite passes were selected on the condition of crossing the equator between 11 and 13 hours local time in a longitude range from 60° - 90° West. Only eleven values were available for the initial comparison, but the variability of the observed values from one pass to another enabled some tentative conclusions to be drawn. For these eleven passes the mean satellite altitude was 500 km.

Table 1 shows the observed values. The variables given in consecutive columns are:

D, Date of selected satellite pass;

T, Time of pass over magnetic equator, U. T.;

S gamma, at the satellite, the estimated amplitude of the "trough" in Difference Field for a pass over the magnetic equator;

H_1 gamma, at Huancayo, defined as H at time T less a night-time value (the night-time value was taken as the mean for the hour 00 to 01 local time on date D and the hour 00 to 01 on date D + 1);

H_2 gamma, at Pilar, defined as for Huancayo;

X gamma, Jet field, taken as the difference $H_1 - H_2 = X$.

Table 1

Observed Values

D Date	T hr min	S gamma	H_1 gamma	H_2 gamma	X gamma
1967					
Oct 4	15 53	12	150	64	86
4	17 30	13	96	46	50
5	16 19	32	170	29	141
8	16 02	19	147	32	115
1968					
Jan 28	17 28	13	125	84	41
29	17 52	21	195	84	111
30	16 39	22	173	84	89
30	18 15	12	109	61	48
Feb 1	17 27	17	166	67	99
2	16 13	16	141	75	66
6	16 11	19	118	58	60

RESULTS

Scatter diagrams of H_1 against S show a weak correlation, and of H_2 against S no correlation. However, a plot of X against S suggests a relationship (Figure 1). Taking means and plotting (Figure 2) it is seen that H_2 is independent of S and that H_1 increases linearly as S increases. X is not plotted on Figure 2 but since it is the difference between H_1 and H_2 it is proportional to S. The constant of proportionality is chosen as k so that X = kS. It will be noted that:

(a) The proportionality of X to S is to be expected if both these parameters are variations in horizontal magnetic field due to the extra current in the electrojet, but the accuracy with which the subtraction of the Pilar values eliminates the non-jet field from the Huancayo variation is probably fortuitous, since Pilar is closer to the focus of the normal quiet day current system than to the equatorial electrojet.

(b) The low correlation between H_2 and S (and hence also between H_2 and X) is in agreement with earlier findings (Osborne, 1964).

(c) The value of k could be determined statistically by a comparison between satellite measurements and data from one observatory located under the electrojet but the elimination of back-ground variation (due to the general ionospheric current system and magnetic disturbance) by the subtraction of a value corresponding to H_2 could make the analysis more accurate.

The mean value of k for the eleven observations on which this analysis is based is 4.6 ± 0.4. The value of k must be determined by the geometry of the electrojet system, in particular the distribution of current intensity with width and the depth of induced currents in the Earth.

In order to make comparisons of this type it is necessary that there shall be data available from two observatories at nearly the same longitude, one under the electrojet and the other displaced slightly north or south from the first, for the days for which suitable satellite data are also available. Preliminary comparisons were made between the satellite data and two pairs of stations in addition to Huancayo and Pilar. However, the analysis was uncertain because the number of passes for which comparisons could be made was small and the variability was not large. The plots show points clustered together and the calculated values for k are therefore very tentative. These are given in Table 2. The larger value of k for the Indian sector may be related to the higher average altitude.

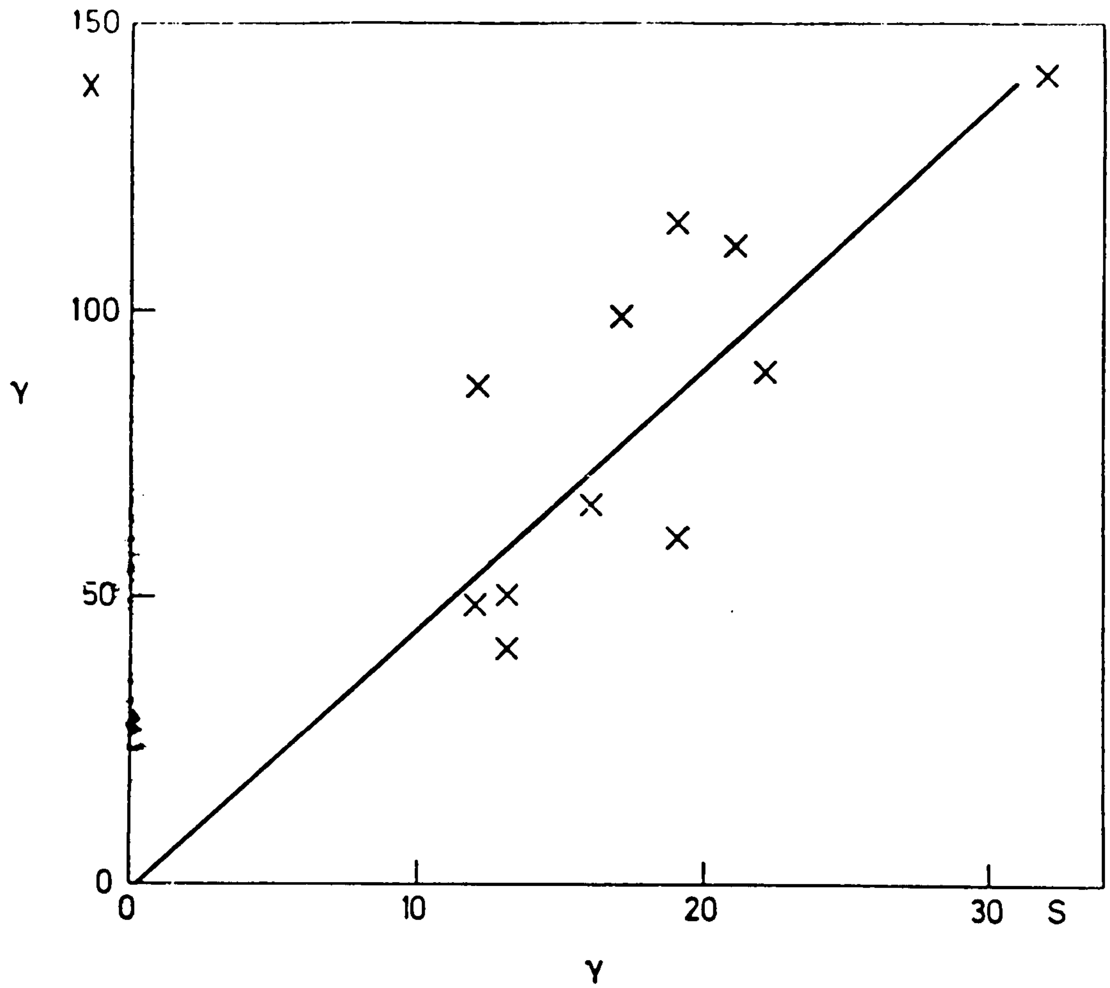

Figure 1

INTERPRETATION

The value for the ratio "k" found for the South American sector was compared with the value for a "Model" electrojet having a uniform Eastward current intensity i, measured as amp km^{-1}, a half-width w km and negligible thickness. It is supposed that this model band current is at an altitude of 100 km and that there is associated with it a westward image current at a depth p km.

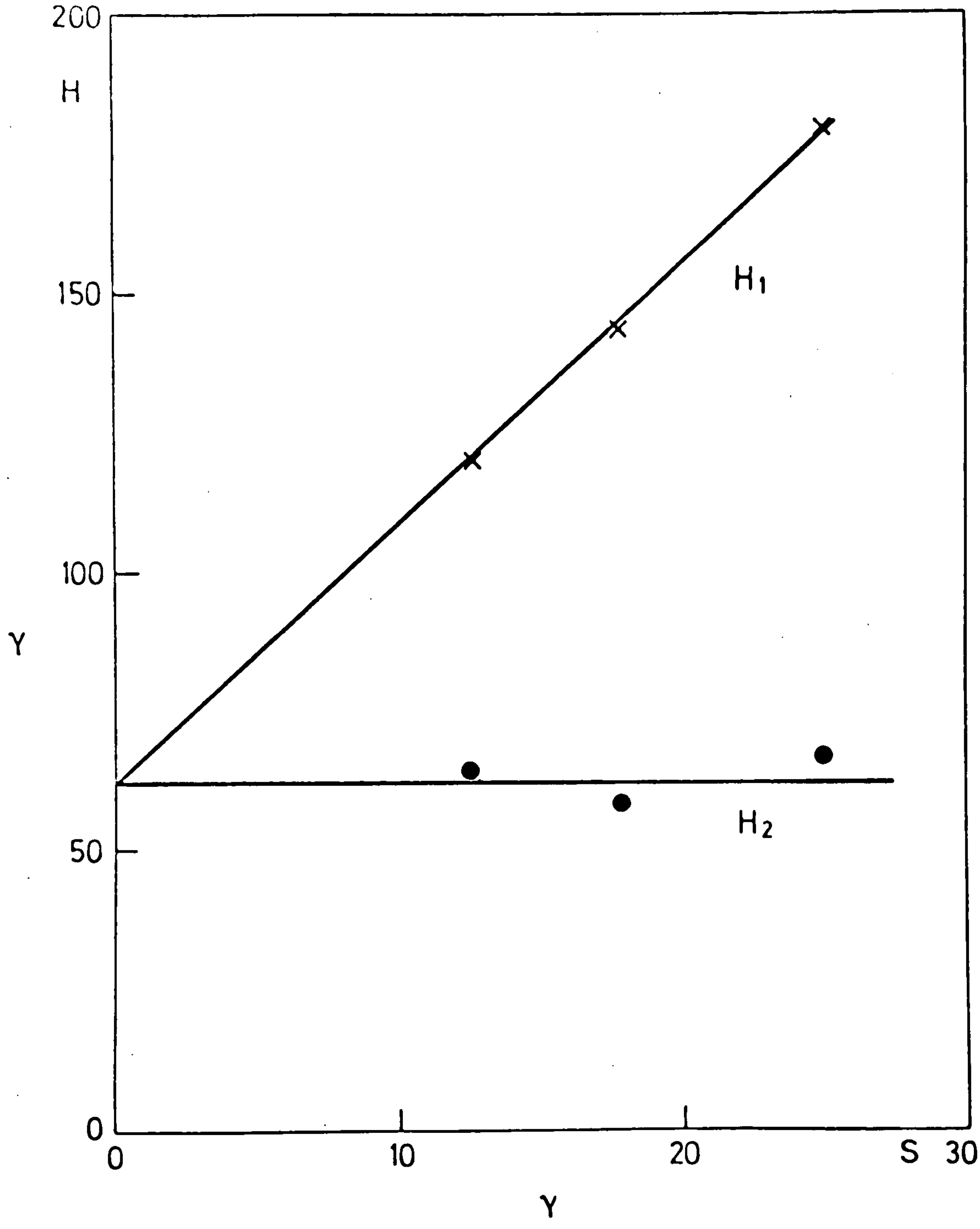

Figure 2

Table 2

Observations and Deduced Values

Sector	Longitude (Approx)	Number of Passes	Mean Altitude	Signature Half-Width	Ratio
	°E		a km	q km *	k
Peru	285	11	500	350 ±15	4.6 ±0.4
India	77	8	650	(420)	7.1 ±0.6
Philippines	125	10	460	340 ±10	5.0 ±0.7

Using the satellite data for passes over Huancayo and the mean value $k = 4.6$ the permissible values of w for assumed values of p were computed. In general there are two possible values of w for any given value of p, as shown by the curve in Figure 3. The shaded areas show the range of values for w when k has a standard deviation from the mean of ± 0.4.

Forbush and Casaverde (1961) give the parameters for a model jet of this type that would fit with their measurements of magnetic variation at a north-south chain of stations across the magnetic equator in Peru for part of the IGY period. They found values for half-width w of 330 km, and for image depth p of 600 km, with a current intensity in the jet i of 142 amp km^{-1}. These model parameters fit observations over a different period from those of the satellite studies, but are represented by a point close to the curve on Figure 3.

THE SIGNATURE WIDTH

The simple model postulated for the jet has three variables (current intensity, half-width and image depth) and the model parameters can be determined uniquely only if there are three independent quantities determined by observations. An examination of the Difference Field plots shows that the width of the signature varies slightly from one pass to another. A value for this was selected - the "half-width" of the signature trough at half its amplitude. This is indicated by the parameter q in Figure 4. Using this value and the known altitude for the satellite pass a numerical relationship between image depth p and half-width w for permissible models was determined. Given these parameters values for the ratio k were deduced. The values of k and q derived from observations enabled the model parameters p and w to be determined uniquely. The current intensity i was found also. Details of the calculations are given in the appendix.

*See figure 4.

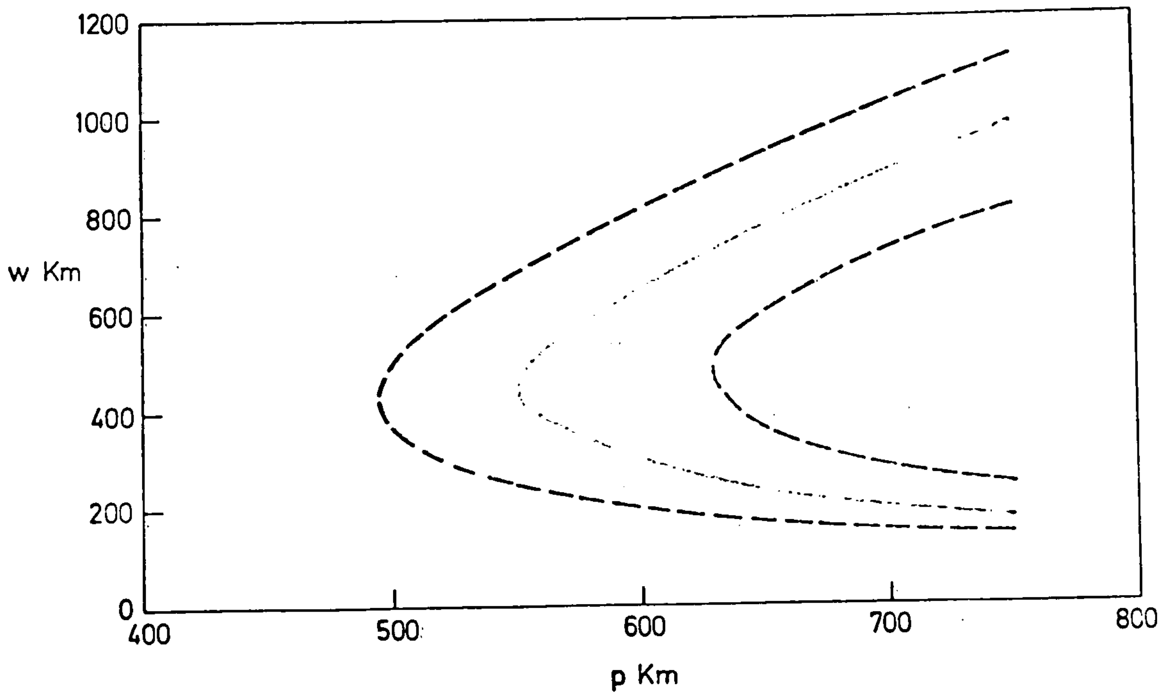

Figure 3

The average parameters for the three sectors are given in Table 3. These results must be considered very tentative due to the relative insensitivity of q for determining w. Also, the passes in each sector are distributed differently about local noon and altitude. However, the results for Peru are similar in value to those suggested by Forbush and Casverde (1961).

Table 3

Model Parameters

Sector	Image Depth	Jet Half-Width	Jet Current Intensity	Total Jet Current
	p km	w km	i amp km^{-1}	I amp x 10^3
Peru	625 ±100	260 ±25	112	58
India	540	280	114	64
Philippines	420 ±100	300 ±20	139	83

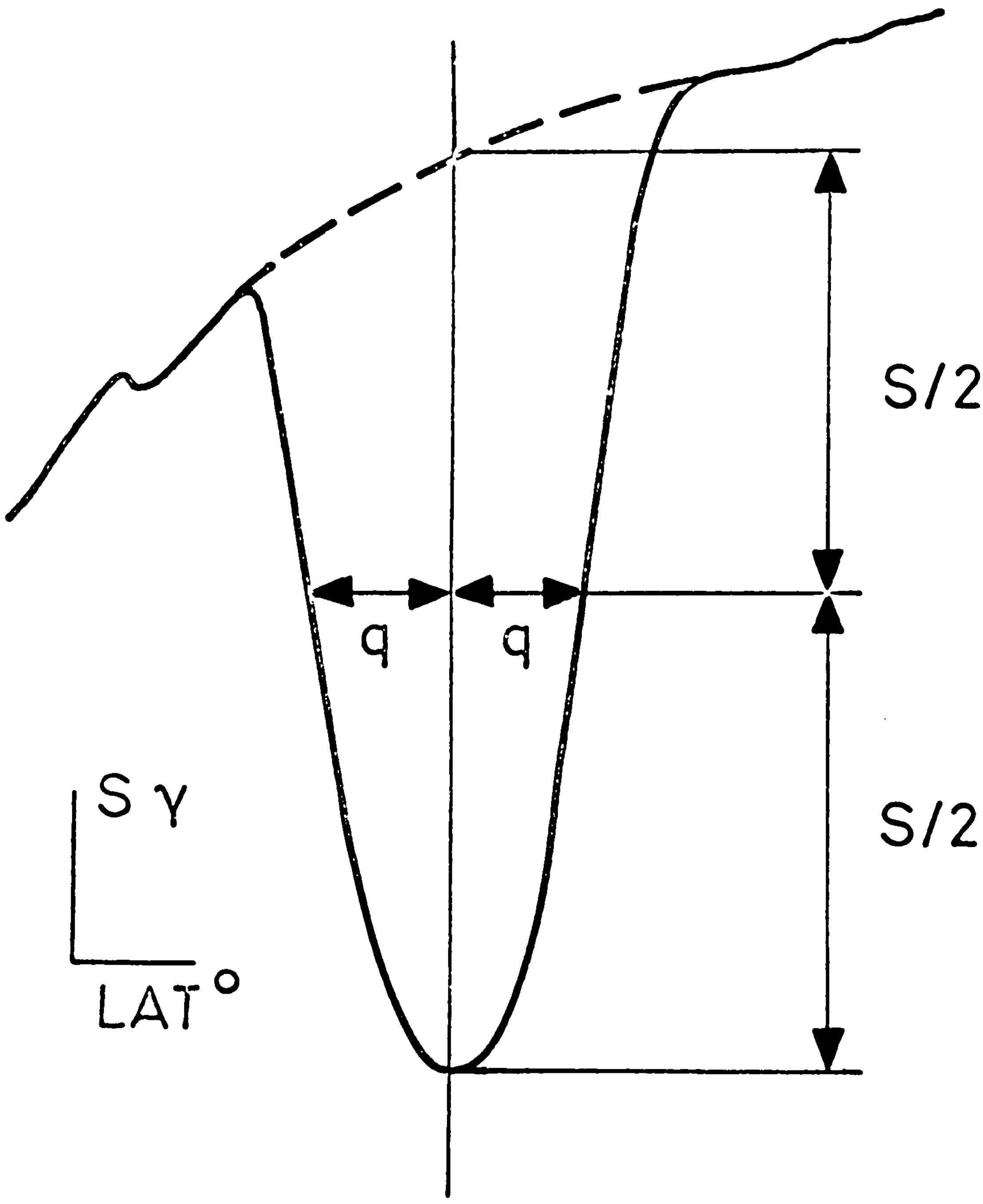

Figure 4

ACKNOWLEDGEMENTS

I wish especially to acknowledge the help of Dr. J. C. Cain of NASA for the provision of satellite data and for encouragement in making this comparison. I would like to thank also the observatories that supplied data on variation through the World Data Centers; the University of Dar es Salaam for support and facilities with which this work was started, and the Inter-University Council for a Fellowship tenable in the Department of Physics at University College London, where the work was completed.

APPENDIX

FIELDS FOR BAND CURRENT MODEL

Consider a uniform thin horizontal sheet of current flowing to the east, with a current intensity, i amp km^{-1}, which is the current density integrated over the vertical thickness of the sheet. For an element of the current subtending an angle dA at 0 (and of infinite length perpendicular to the plane of the diagram) the northward field component in gammas is given by (see Figure A-1).

$$dX = dF \cos A = 2i\, dA/10 \qquad 1$$

If the current sheet is of half width w, centered at P, then the northward field at a point 0 which is x km north of a point vertically beneath P is given by

$$X = \frac{2i}{10} \left\{ \tan^{-1}\left[\frac{x+w}{h}\right] - \tan^{-1}\left[\frac{x-w}{h}\right]\right\}, \qquad 2$$

which may be re-arranged to the form given by Chapman (1951) and Onwumechilli (1959)

$$X = \frac{2i}{10} \tan^{-1}\left[\frac{2wh}{h^2 + x^2 - w^2}\right] \qquad 3$$

Note that if $w^2 > h^2 + x^2$ the angle is greater than $\pi/_2$.

Under the centre of the current band x = 0 and (from equation 2)

$$X = \frac{4i}{10} \tan^{-1}\left[\frac{w}{h}\right].$$

It has been suggested that induced currents in the Earth due to steady currents in the ionosphere are equivalent to an image current system, as though the Earth has an electrically non-conducting surface layer over a perfectly conducting lower region. The image current will be equal and opposite to the ionospheric current causing it. The field at the Earth's surface will be the sum of the field due to the external current, derived already, and the field due to the image current of current intensity -i at a depth p. Then

$$X = \frac{4i}{10} \left\{ \tan^{-1}\left(\frac{w}{h}\right) + \tan^{-1}\left(\frac{w}{p}\right)\right\}, \qquad 5$$

or

$$X = \frac{4i}{10} \tan^{-1} \left\{ \frac{w(p + h)}{ph - w^2} \right\} \qquad 6$$

Note that h and p are both taken as positive. At a satellite vertically above the axis of the band current system the horizontal field predicted by the model is:

$$S = \frac{-4i}{10} \left\{ \tan^{-1} \left(\frac{w}{a_1} \right) - \tan^{-1} \left(\frac{w}{a_2} \right) \right\} \qquad 7$$

where $a_1 = a - h$ and $a_2 = a + p$, a being the altitude of the satellite. The negative sign indicates only that the direction of S is opposite to that of X and may be omitted. Rearranging

$$S = \frac{4i}{10} \tan^{-1} \left\{ \frac{w(a_2 - a_1)}{a_1 a_2 + w^2} \right\} \qquad 8$$

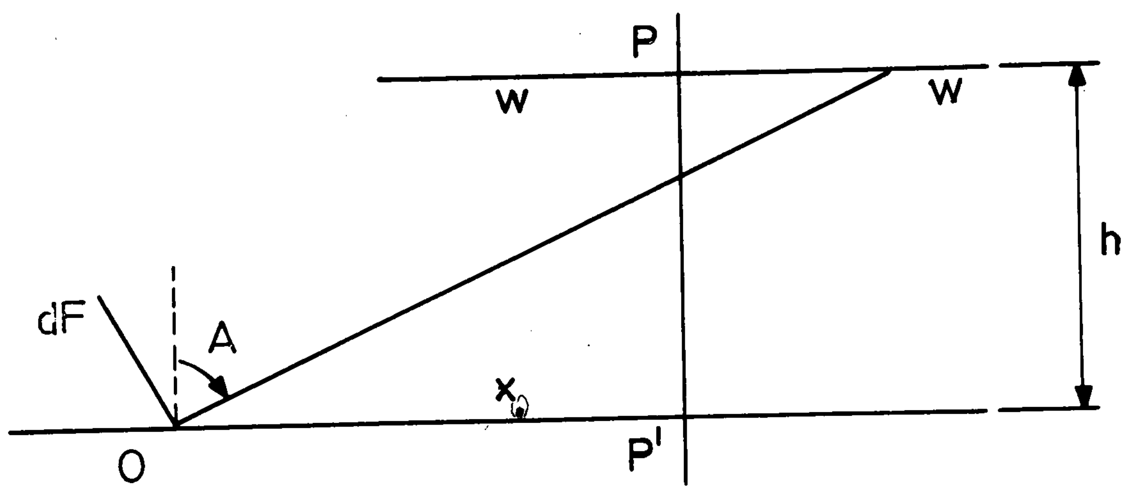

Figure A-1

From equations 6 and 8 the ratio $k = X/S$ may be derived for different model parameters. We take $h = 100$ km. For given values of a and k there is a series of values for w against p that indicate permissible model parameters. In this way figure 3 was obtained. To relate q to the model parameters we require an expression for the horizontal field S' at a point in the satellite orbit displaced x km northward from the centre of the system. It is supposed (1) that the satellite orbit is approximately horizontal over the distance x and (2) that the Earth's main field is sufficiently close to the horizontal over this distance for the horizontal field deduced from the model to be compared significantly with the difference field measured at the satellite. Deriving S' in the form given for X in equation 3 and combining the angles, we have

$$S' = \frac{2i}{10} \tan^{-1} \left\{ \frac{2wa_1 (a_2^2 + x^2 - w^2) - 2wa_2 (a_1^2 + x^2 - w^2)}{(a_1^2 + x^2 - w^2)(a_2^2 + x^2 - w^2) + 4w^2 a_1 a_2} \right\} \qquad 9$$

When $x = q$, $S' = S/2$. Comparing equation 9 with equation 8 it is clear that the angles must then be equal. (The use of different identities in the equations gives this simple result). If w^2 is ignored in comparison with $(a_1^2 + a_2^2)$ simplification gives

$$w^2 = \frac{q^4 + q^2 (a_1 + a_2)^2 - a_1^2 a_2^2}{a_1^2 + a_2^2} \qquad 10$$

Values for q and a_1 are known. Arbitrary values were chosen for p, giving values for a_2 and hence (by computation) for w and k. The requirement that the value of k deduced from the model should agree with that calculated from observation enabled p and the other model parameters to be determined.

SUMMARY AND FUTURE WORK

Joseph Cain
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Ebun Oni

The OGO-4 and 6 (POGO) magnetic field results for the equatorial electrojet indicate that while the present models are approximately correct, the possibility of a westward component must be incorporated.

The scatter diagrams of the POGO amplitudes and surface data show a correlation. That is very good on the average but has numerous exceptions. The ratios between the amplitudes estimated from surface data and those at 400 km altitude are as follows:

India	5 to 8
East Africa (Addis Ababa)	4
Central Africa	3
West Africa (Nigeria)	3
South American (Huancayo)	5
Philippines	5

The variation in the ratio is likely to be due to the conductivity structure of the earth in the various zones.

The presence of the counter electrojet on occasion and the frequent deviations of the jet signature in ΔF from that predicted by a simple model implies that a fuller explanation is still lacking. This uncertainty is reinforced by the fact that the surface/satellite ratios are highly variable from time to time, whereas they should be definitively relatable.

The state of research in this area has now reached a new level where the description and modelling can and must be worked\out in terms of physical principles. The POGO data give us a comprehensive view of the electrojet above the ionosphere which, when coupled with surface observation, should allow a separation of the contributions from the magnetosphere and those from the ionosphere. Further, the induced contribution should be investigated. This last factor should now be included using realistic models of conductivity instead of the image plane approximation.

A general plan to attack this subject might include the following:

(1) Vector field observations should be planned for any future observations of the electrojet from satellites.

(2) Determine the planetary S_q during the days of the POGO traversals so that its effect at the equator can be estimated separately from its enhancement by the electrojet. This could be done first using only surface data and then in combination with the satellite results. In this line, improve knowledge of baseline for measuring the electrojet signature amplitude and thus estimate the direction of the current on either side of the electrojet peak.

(3) Using ΔF profiles and surface data to determine electrojet parameters with a sufficiently sophisticated model to describe the variations including their change with altitude.

(4) Incorporate the results of the above study into both electrojet and S_q theory. Also, make comparisons with magnetic and plasma observations as are simultaneously available from the ground and from other spacecraft in the magnetosphere.

The results of such studies that could be foreseen for a future equatorial symposium are as follows:

(a) Theoretical understanding of the electrojet.

(b) Estimates of the electric field variations from day-to-day in the electrojet region.

(c) Interpretation of the electric field variations according to the contribution from wind changes or magnetospheric sources.

(d) Estimates of the upper mantle conductivity structure in equatorial regions.

The magnitude of these studies in such that they should be undertaken by numerous groups. Much of the work requires dealing with numerical computations requiring modern computing equipment. All of these studies involve deriving sophisticated mathematical formulations with only those approximations as are absolutely justified. The models must include as much detail as the magnetic variability.

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SELECTED CRITICISMS

In order to give the reader the benefit of some of the reviewers comments and to outline the areas of disagreements, we are including some of the criticisms without rebuttal. We hope that this will aid in understanding the physical processes surrounding the equatorial electrojet by stimulating further work and publications on this subject and that more information can be derived on the earth's interior, ionosphere, and magnetosphere from a study of the magnetic data.

The Editors

A. THE POGO DATA - J. Cain and R. Sweeney

Since the delta-F of the profiles is the difference between the observed F and the F of a given model, what is the significance along the profile of latitude ordinarily shown in the Figures, (1) of a "spatial" variation so that the F of the model is subject to an error which varies with latitude, (2) of a "temporal" variation so that the observed F contains a variation of the "perturbation" type, which cannot be negligible during the 15 minutes that the profile by the satellite lasts?

On the one hand, it is unquestionable that the signatures observed in the daytime, whose minimum agrees with the "dip-equator", are in general the signatures of the equatorial electrojet. On the other hand, however, any quantitative measurement of the amplitude of these signatures seems to be subject to genuine inaccuracies as long as the author cannot explain the significant difference that exists between the day pass and the night pass, even during a relatively calm period.

Since the amplitudes of the signatures are most frequently less than 30 gammas (only about 60 are equal to or greater than 30 gammas), while the majority of them are less than 15 gammas, we can justifiably ask whether Figure 16 is significant and whether any conclusion relative to the induced effects as a function of the longitude can be drawn.

The last sentence of the first paragraph of the abstract: "It was speculated that this could be due to a less conducting upper mantle in this area" should be reconsidered. This summary derives from the discussion on page 23 which does not fit all the facts. A less conducting upper mantle in the region of 50° to 140° East Longitude would make the POGO field higher and the ground field smaller than expected. This should make the ratio of the field at the ground to the field at 400 Km altitude smaller in India than in any other region. To the contrary, this ratio determined at India by both Osborne and Kane is higher than in any other region. It is therefore unlikely that upper mantle conductivity can explain the observations.

B. COMPARISONS WITH SURFACE DATA

1. India - R. P. Kane

The method of computing electrojet field at Trivandrum is questionable as it still contains a little of the worldwide S_q. Consequently, it would have been better to compute the regression lines which would demonstrate an intercept where it exists than the adopted method of joining the centroid to the origin. It might have been better to subtract the Alibag from the Trivandrum hourly values. Note that in the analysis of the Central African Data

$$\Delta H = 2.9 \Delta F + 0.1$$

Here the intercept is practically zero because the worldwide S_q, which is the cause of such intercept, has been removed. The author should state somewhere that some residual worldwide S_q in the difference field can effect the results.

While the author specifies that he is using different local times (between 0900 and 1600) he does not say in the case of the pairs of values employed (delta-Sd_I, and Pogo amplitudes) what the maximum differences in longitude are which he has allowed for between Trivandrum and the satellite.

Two other points seem to be worthy of criticism. First <u>of all</u>, normalization for altitude is accomplished by means of a factor ($ALT/\overline{ALT}$) where ALT is supposed to the altitude of the satellite. If it really is the altitude relative to the ground, as the reader is justified in supposing, this is a mistake. It is the quantity $(ALT-h)/(\overline{ALT}-h)$ which should be used, where h is the altitude of the electrojet. Moreover, selecting as the mode of normalization a law corresponding to the reciprocal of the distance seems to me to be a gross simplification (much too rapid a decrease). Secondly, the author is using the quantity Sd_I = H(TRI) - H (ALI) + Sq (ALI), or Sd_I = H(TRI) - (H (ALI) - Sq (ALI)). It is not clear why it is necessary to correct the total amplitude for Trivandrum by the variability of Sq at Alibag. In the final analysis the author is not using "the actual electrojet strength", but the total amplitude. Since the slope values which he gives are those of lines joining the center of gravity of the ΔSd_I points to the origin and not the lines of regression, it is clear that the slopes are much higher than those from the other comparisons.

B. 5 Ibadan, Nigeria - E. Oni

Regarding the statement on page 51: "Different authors who had considered the problem followed Chapman's lead in .... the use of an infinitely conducting layer at the same depth to estimate its induction effect. All the methods used so far by Forbush and Casaverde (1961), Onwumechilli and Ogbuehi (1967), Fambitakoye et al. (1972), and Osborne (pg. 59), follow the same pattern". This statement is incorrect since Walter Kertz, Olaf Hartmann, Onwumechilli and Ogbuehi, etc.* have used the integral transform method to compute the induction effect of the electrojet. This method does not depend on the image of the electrojet. With it the induction effect can and has been computed without the assumption of any model. Fourier series have also been used independent of image and modelling. The results show that the induction effect of the electrojet relative to the inducing field is rather less than the third usually found for the induction effect of worldwide S_q.

On page 52: "The slope of Fig. 2 was taken and multiplied by a factor of 1.5 to reduce to jet axis value." We understand that the factor of 1.5 is appropriate for Zaria, but Zaria is still 1.4° from the dip equator. A higher factor probably nearer to 2.5 should be used to reduce to jet axis value.

The ΔH at Ibadan is largely worldwide S_q(H) and contains relatively small electrojet field. This is because Ibadan is too far from the dip equator (about 3° away and therefore at the edge of the electrojet). At this distance ΔZ is a much better parameter for the electrojet field than ΔH. Compare Fig. 2 of this paper which shows a worldwide S_q intercept of about 45 gammas while ΔH is from about 50 to 80 gammas. The relative average electrojet field is therefore

$$\frac{65 - 45}{65} = \frac{20}{65} \text{ less than } \frac{1}{3} \text{ of } \Delta H.$$

On page 56: "The very poor correlation between POGO data and the ground data as shown by the scatter diagram of Fig. 1 is due to the stronger contamination of the ground data by the induction of the electrojet in a relatively complex earth structure of finite conductivity, as compared with the satellite data". The reviewer disagrees with this conclusion for the following reasons:

(a) The induction effect itself is a small fraction of the inducing field.

(b) The induction effect of the diurnal variation depends largely on the distribution of subterranean conductivity and the 24-hr., 12-hr., 8-hr., and 6-hr. harmonic components, and these are constant for Ibadan observatory. The induction effect at Ibadan and at the satellite over

*See Onwumechilli, 1967, pp. 477-483.

Ibadan should therefore not change radically from day to day, except in proportion to inducing field.

(c) The comparisons of ΔH at Addis Ababa, Huancayo, Trivandrum, Phillipines and Central Africa have not encountered a similar lack of correlation.

(d) The scatter of the points in Fig. 1 and the lack of correlation are due to the fact that the ΔH used is not a sufficient indication of the electrojet. The bulk of it (about 45 gammas) is worldwide S_q agreeing with the 44 gammas found by Gouin at Addis Ababa, another African station like Ibadan. It has been demonstrated, Osborne (1964), Forbush and Casaverde (1961), Ogbuehi, et al.* that the worldwide S_q does not correlate with the equatorial electrojet. That is the cause of the scatter and lack of correlation in this paper.

*See Onwumechilli, 1967, p. 498.

B. 6 South America, et al - D. Osborne

The second part of the paper seems to be highly speculative. The method is certainly ingenious, but is it applicable to data that are so poor? The experimental data which are used are the parameters k and q. The first suffers from a double deficiency: an error in the measurement of the amplitude of the signature S in the altitude, and an error in the definition of X (difference between H_1 and H_2), which is certainly insufficient because H_2 does not represent the value which would be observed at the magnetic equator in the absence of the effect of the electrojet.

C. SUMMARY AND FUTURE WORK - J. Cain, A. Onwumechilli, P.N. Mayaud, and E. Oni

Reading these papers together, one is struck that one of the major contributions of these comparisons of ground with POGO data is the proof that a threshold of the ground data exists below which there is no electrojet field. In Osborne's Fig. 2 that threshold is shown equal to the worldwide S_q outside the influence of the electrojet. In Fambitakoye's regression line where the worldwide S_q has been removed, the threshold is zero. This seems to settle the controversy whether the observed field at the dip equator is made up of two component parts (worldwide S_q and electrojet fields) or is one integral and inseparable whole. We may never get a more direct proof than these POGO comparisons.